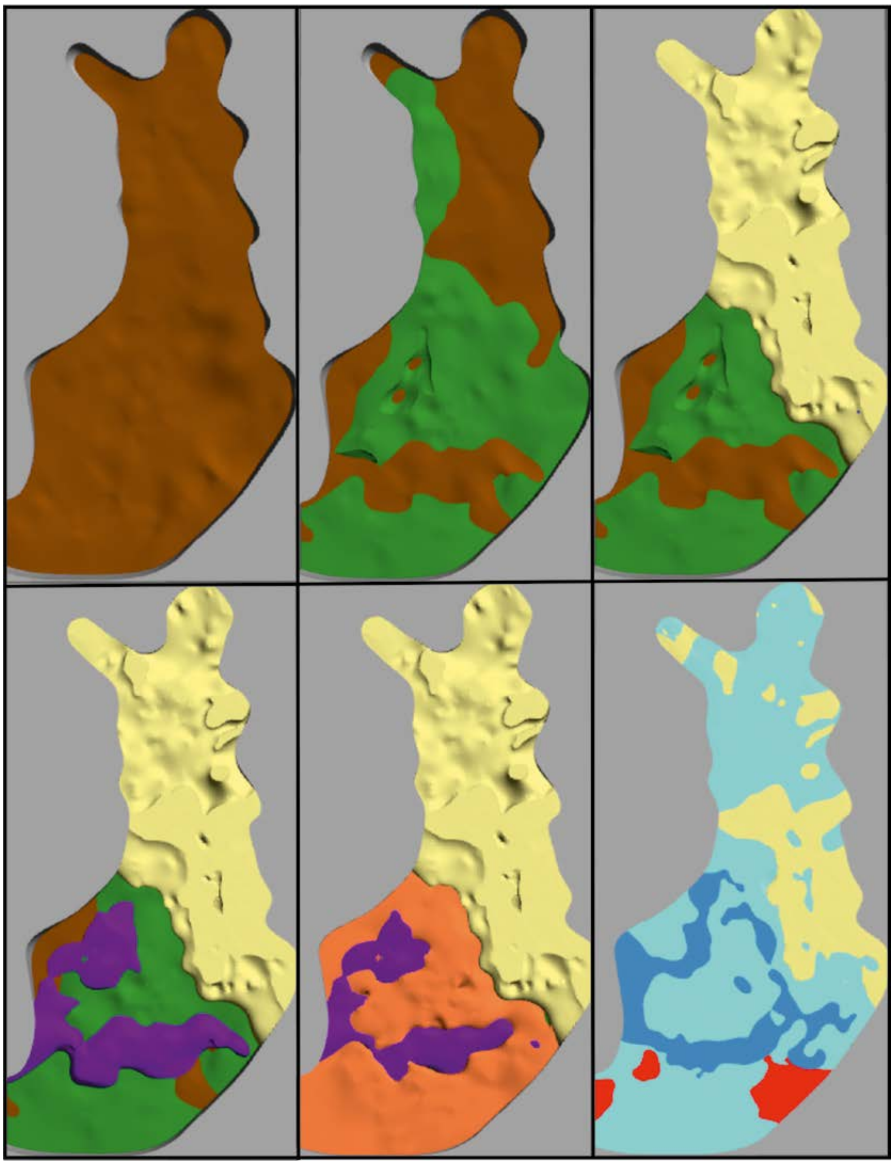
Geological Survey of Finland

2021

3D crustal model of Finland based on conceptual 2D geological cross-sections

Raimo Lahtinen, Paula E. Salminen and Eevaliisa Laine

GTK Open File Research Report 20/2021



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Unless otherwise indicated, the figures have been prepared by the authors of the publication.

Front cover: Superimposed layers of the 3D crustal model. Photo by the authors.

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Mapping in areas with limited topographic variation, such as Finland, has changed in recent decades. Deep-penetrating data have made it possible to see inside the crust and 3D mapping has become a routine procedure. As a framework to support near-surface studies, we also need crustal-scale models. Here, we present one approach based on conceptual geological knowledge and geophysical data. Finland has been covered with several 2D cross-sections cross-cutting major tectonic boundaries, such as the Archean–Proterozoic collision boundary. The cross-sections are grouped into five main groups: 1) the Archean–Proterozoic boundary (AP), 2) the Norrbotten–Karelia boundary (NK), 3) the Kola–Karelia boundary (KK), 4) Central Lapland (CL) and 5) Svecofennia (SV). The interpretations and cross-sections described in this report are conceptual, based on selected tectonic models, and should be considered as such. The basic unit is a crustal unit, which is an informal crustal-scale geological unit. The focus is on Paleoproterozoic tectonic evolution, and the Archean amalgamation history is not discussed.

The sketched 2D cross-sections are used in this report as raw data to create a 3D crustal model. Selected cross-sections are presented as a fence diagram and as digitized lines using simplified crustal units. Interprid GeoModeller was used to create the 3D crustal model based on simplified versions of the cross-sections. Competing tectonic models exist and models may significantly evolve. Thus, 3D models employing different approaches should also be tested. Nevertheless, any 3D crustal model should be easily iterated if the basics of the tectonic model change or new data and interpretations become available.

Appendices:
Appendix 1: 3D crustal model (Crustal3D_version1.0.pdf)
Appendix 2: Geological conceptual 2D cross sections

Keywords: Finland, 3D model, geology, cross-sections, tectonics

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CONTENTS

1 INTRODUCTION AND RATIONALE

Precambrian shield areas are stable regions of the earth's crust and are often characterized by a flat topography and scarcity of bedrock exposures. This is also the case for Finland, in the Fennoscandian Shield, where most of the Precambrian bedrock is covered by overburden and exposed bedrock lacks the third dimension, also making direct geological interpretation to depth difficult. Nevertheless, a 3D image of the present crust is needed to understand the complicated evolution responsible for its formation. Traditionally, the crust has first been visualized using 2D geological cross-sections, which are based on conceptual geological knowledge and geophysical data. This is a non-linear and complex process that involves the application of geological and geophysical rules and experience.

Thus, creating a crustal-scale 3D model is a challenging task and success depends on the amount and quality of surface geodata and crustal-scale geophysical data. Surface geological data can be interpreted to depths in the order of a few kilometres, but deeper knowledge of continuities is derived from geophysical data, which are method dependent, measuring different parameters (e.g., gravity, magnetics, reflectivity, conductance). In areas affected by a single compressional or extensional event, the related geometries are relatively easy to decipher if multisource data are available. The situation is more complex in multiply deformed regions where discontinuities are common both at the surface and in the crust. A conceptual approach is based on information from the surface and a tectonic evolution model explaining how the present crustal configuration has formed. At the same time, the 3D model should fit the observed characteristics (data). Of course, several alternative tectonic models might fit the data, and thus several 3D crustal models could be equally justified. However, any 3D crustal model should be easily iterated if either the tectonic model changes or new data become available.

Finland has excellent geological, isotope geology, geochemical and geophysical data sets (GTK_Geodata) and also good coverage of deep geophysical data (Fig. 1). The main challenges are the poor exposure of outcrops (average 3.8%) and flat surface, limiting direct 3D information. We have divided the country to several cross-sections (Fig. 2) cross-cutting major boundaries, such as the Archean–Proterozoic collision boundary. Here, we present sketched 2D interpretation cross-sections, which are then used as raw data to create a 3D crustal model. The interpretations and cross-sections described in this report are conceptual and should be considered as such. As the 3D crustal model of Finland will be an evolving model, the metadata, and changes to these data, will be presented in this context.

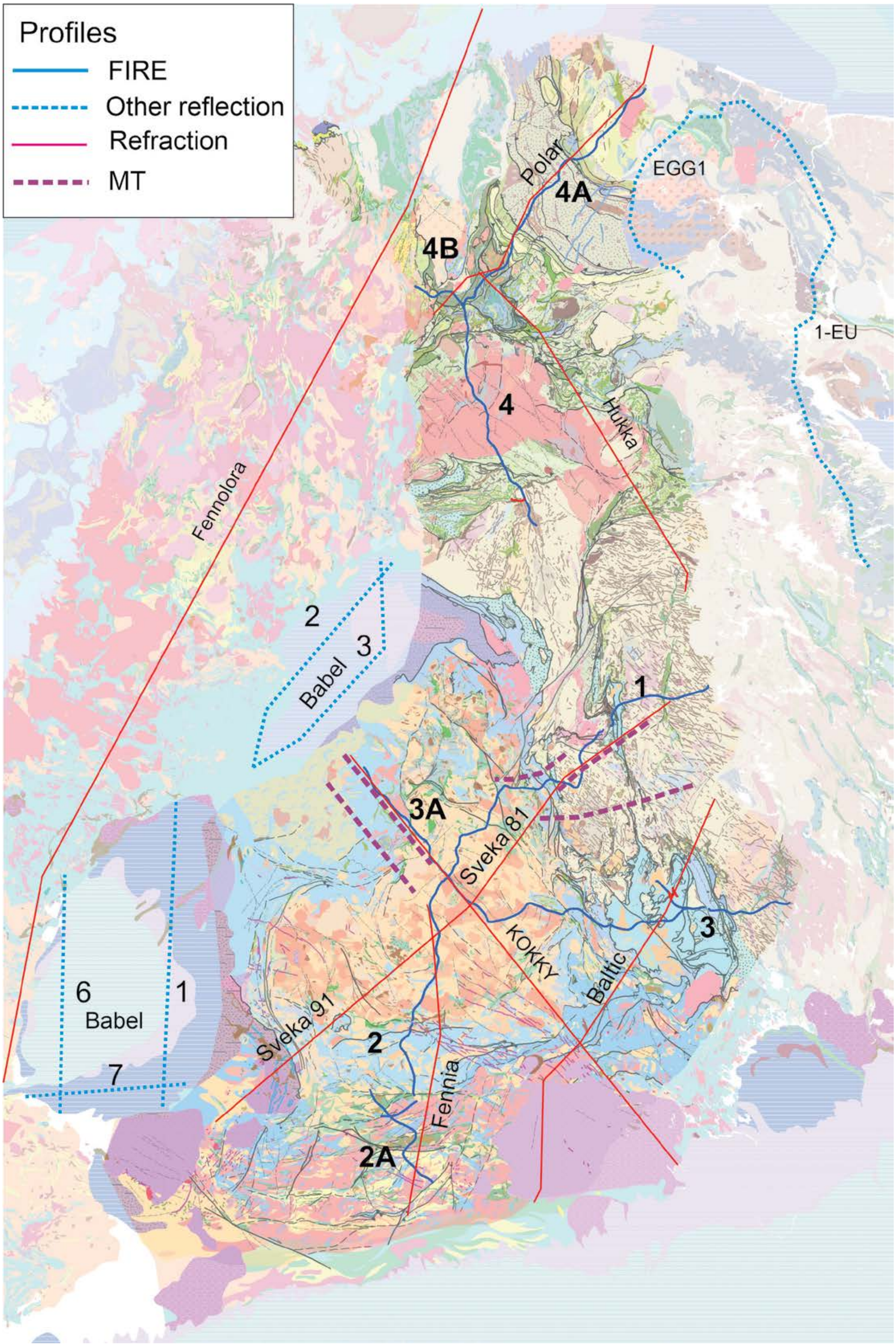

Fig. 1. Deep geophysical data in Finland and adjacent areas (see text for references). The crustal conductance model 0–60 km (Korja et al. 2002) covers the whole of Finland. Geological background for Finland from Bedrock of Finland – DigiKP. Surrounding areas from Koistinen et al. (2001).

2 SKETCHED CROSS-SECTIONS

2.1 Quality classification of the cross-sections

The sketched geological cross-sections have been classified into quality classes based on available information (see below). In particular, reflection seismic data, e.g., FIRE, have been used in several crustal-scale interpretations (e.g., FIRE Special Paper, Kukkonen & Lahtinen (eds) 2006, Korja & Heikkinen 2008) and they have also been utilized here. The difficulty in interpreting deep reflections arises from the tectonic concept used, as seen, for example, in the interpretations of the FIRE 3 profile (Fig. 1), where the same reflectors have been interpreted as compressional (Sorjonen-Ward 2006, Lahtinen et al. 2016) and extensional (Korja et al. 2009, Nikkilä et al. 2015).

Cross-section quality classes (Table 1):

A: Reflection and refraction seismic data and available interpretations;

B: Reflection or refraction seismic or MT data and available interpretations;

C: Only geological and potential field data available.

Geological and potential field data, and also FIRE reflection data, are available as data sets, but for the other information, we have used interpretation figures from publications when sketching the cross-sections. As such, the locations are not accurate, especially in the vertical dimensions, and in the case of class C cross-sections they are, apart

Table 1. Cross-sections.

Profile	QC[1]	Data[2]	Selected key references
AP 1	A	SVEKA81, FIRE 1, MT	Korja et al. (2006), Vaittinen et al. (2012)
AP 1a	B	MT	Vaittinen et al. (2012)
AP 1b	C		
AP 1c	C		
AP 2	B	FIRE 3a, 3,	Sorjonen-Ward (2006)
AP 3	B	Baltic, gravity model	Janik (2010), Elo & Korja (1993)
AP 3a	C		
NK 1	B/C	Partly FIRE 4B	Patison et al. (2006), Niiranen et al. (2014a)
NK 2	B	close to FIRE 4	Niiranen et al. (2014a)
NK 3	C		
NK 3a	C		
NK 4	C		
KK 1	A	Polar, FIRE 4, gravity model	Gaál et al. (1989), Patison et al. (2006), Elo (2006), Janik et al. (2009), Niiranen et al. (2014b)
KK 1a	C		
KK 2	B/C	Partly EGG 1	Sharov (1997), Mints et al. (2007)
CL 1	B	FIRE 4	Patison et al. (2006), Silvennoinen et al. (2010)
CL 2	B	HUKKA	Tiira et al. (2014)
SV 1	B	FIRE 3, MT-PE, Babel 3	Sorjonen-Ward (2006), Korja & Heikkinen (2005), Chopin et al. (2020)
SV 1a	B?	MT, MT-B2	Chopin et al. (2020)
SV 1b	C		
SV 2	A	Fennia; FIRE 1, 2; MT	FENNIA Working Group (1998), Korja et al. (2006), Nironen et al. (2006)
SV 2b	C	MT	
SV 3	B/C	partly FIRE 2, Fennia	FENNIA Working Group (1998), Nironen et al. (2006)
SV 3a	C	MT	
SV 3b	C		
SV 3c	C		
SV 4	B	SVEKA91	Luosto et al. (1994)
SV 5	C		
SV 6	C		

[1] QC = Quality class

[2] FIRE data from Kukkonen et al. (2006); MT data from Korja et al. (2002)

from the surface data, very speculative. In an ideal situation, we would have access to all the original data in 3D, including the measurement uncertainties, but at present the user must simply consider these limitations.

2.2 Cross-sections

2.2.1 General

The cross-sections are grouped into five main groups (Fig. 2): 1) the Archean–Proterozoic boundary (AP), 2) the Norrbotten–Karelia boundary (NK), 3) the Kola–Karelia boundary (KK), 4) Central Lapland (CL) and 5) Svecofennia (SV). These groups are linked to the tectonic provinces in Finland (Kohonen et al. 2021). The AP boundary cross-sections include the central part of the Karelia Province and its boundary with the Central Finland Province and Southwestern Finland Province. The NK and KK boundaries include parts of the Karelia province and its boundaries with the Norrbotten and Kola Provinces, respectively. The Central Lapland cross-sections occur inside the Karelia Province, and the Svecofennia cross-section includes both the Southwestern and Central Finland Provinces. For the main groups, we present the selected tectonic model that we consider to best explain the current crustal structure. We also list other proposed models but do not discuss them in detail. Thus, the selected tectonic model is in a key position and the reader is referred to the other models to obtain a more comprehensive view of the possible variations in the conceptual tectonic evolution model used here.

The cross-sections within the five groups are divided into main cross-sections and sub-cross-sections presented in the Appendix 2. The cross-sections are constructed using crustal units and the main structural elements.

A crustal unit = an informal crustal-scale geological unit.

The crustal units, starting from the surface, include DigiKP map units or a collage of DigiKP map units described in the Finstrati database (Bedrock of Finland – DigiKP). Inferred crustal units without surface expressions are briefly described with the main groups. While the surface data are composed of mappable units, the deep crustal units are derived from the interpretation of deep geophysical data combined with surface geology (e.g., stratigraphy, structural geology) and geochemical and isotope geology data from igneous rocks. Examples of the latter include kimberlite xenoliths sampling the whole crust and granitoids derived from different depths and various sources. The combined interpretations are derived from numerous publications that are presented in reference lists but not discussed in detail. As such, the interpretations of the subsurface data and igneous fingerprinting are highly tentative. Thus, the boundaries of deep crustal units are poorly defined, and the geological interpretation of their origin is dependent on their physical properties and the tectonic model used.

The main structural elements presented here are currently informal. Major horizontal movements have occurred along transcurrent faults, which are typically multiply reactivated and can have a long history. The reactivated rift faults indicate basin inversion during collision, and the “orocline” faults are inferred thrust and reverse faults related to oroclinal buckling in Svecofennia (Lahtinen et al. 2014, 2017). Other faults are unseparated major faults.

We have simplified the cross-sections, and the crustal units used are based on their importance in understanding how the crust has formed. Thus, the FinStrati (Bedrock of Finland – DigiKP) units used in the cross-sections vary from the supergroup/suite level to the formation/lithodeme level. The Archean crustal units, although stacked in the Paleoproterozoic collision zones, appear to have had a typical thickness of ca. 40 km before rifting, and we thus consider them as a single unit without any depth separation into upper, middle and lower crust. In the future, the Archean supracrustal belts should be included in the cross-sections and the Archean amalgamation history modelled. In addition, in this stage we have combined all the Paleoproterozoic supracrustal cover rocks and the intruding igneous rocks as cover sequences on the Archean crust. The separation of the other Paleoproterozoic crustal units into age groups is explained when discussing cross-section groups.

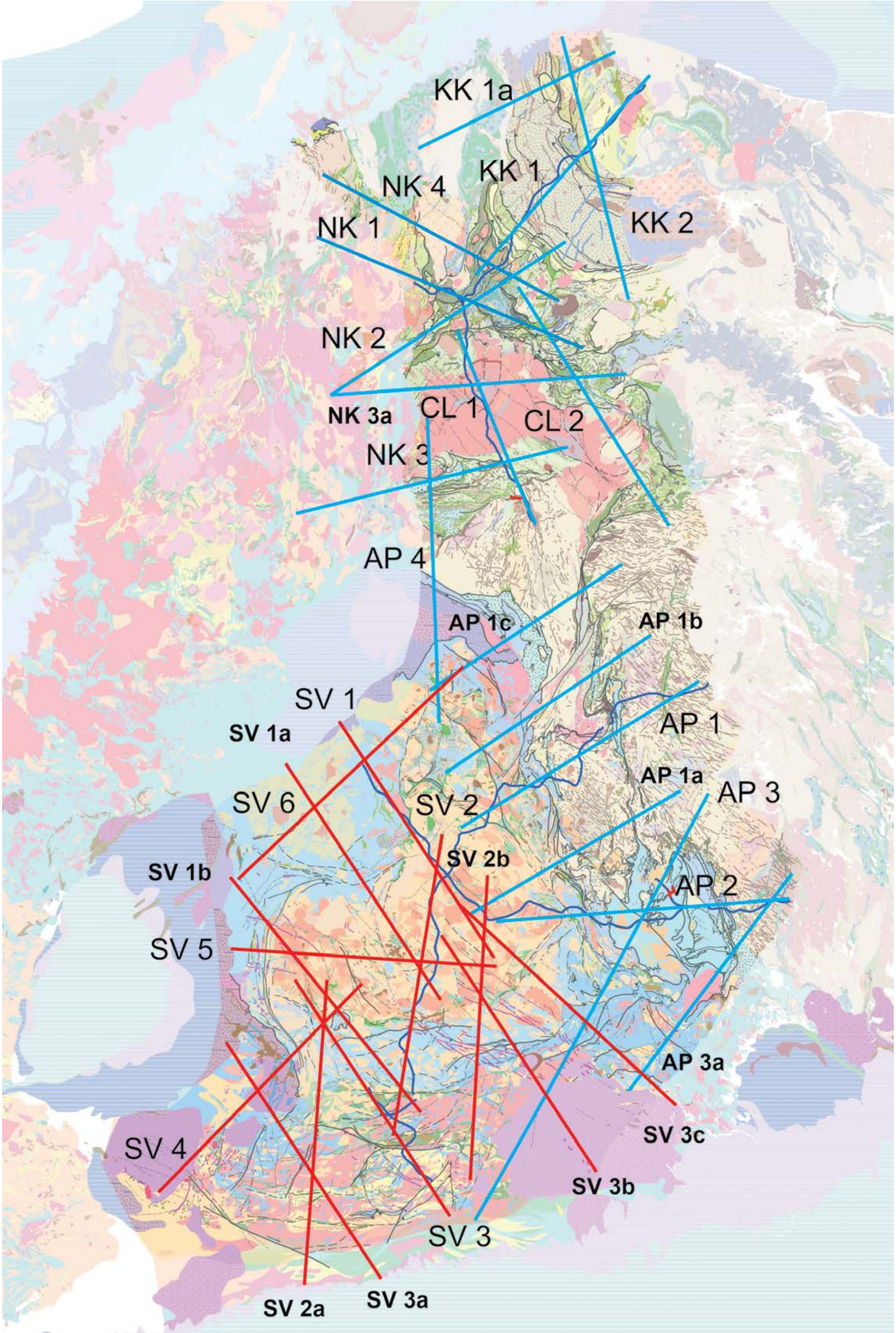

Fig. 2. Locations of the sketched 2D cross-sections. See Figure 1 for background data.

2.2.2 The Archean–Proterozoic boundary (AP cross-sections)

2.2.2.1 Tectonic model

A characteristic feature of the lithosphere in Finland is the exceptionally thick crust and lithospheric mantle at the Archean–Proterozoic boundary in central Finland. The crustal thickness is 15–20 km in excess of normal Archean to Paleoproterozoic crust found globally. The selected conceptual tectonic model attempts to explain the observed surface geology and crustal-scale features, and how the thick crust could have been achieved and balanced.

Continental breakup of the Karelia craton occurred at 2.1–2.06 Ga and large amounts of mafic magmatic underplate formed in the extended lower crust. New spreading within the pre-existing passive margin at 1.98–1.93 Ga (Jormua, Outokumpu) led to a marginal basin locally exposing Archean lithospheric mantle. During the initial continent–arc collision, ophiolite obduction and the formation of a foreland fold and thrust belt occurred at 1.92–1.91 Ga. Subsequently, the subducted slab steepened strongly at a high angle and finally detached, and shallow slab breakoff occurred. Mantle–crust decoupling of the Archean lithosphere took place and a crocodile jaw formed, where the Paleoproterozoic arc rocks (west) were partly buried beneath the bounding Archean continent (east). The AP boundary was severely affected by a deformation event at ca. 1.885 Ga followed by voluminous magmatism at 1.88–1.87 Ga. Renewed shortening events at ≤1.87 Ga continued until ca. 1.79 Ga. All these events led to thickening of the AP collision zone through magmatism and horizontal shortening, seen in vertical crustal-scale features. The occurrence of thick mafic lower crust and cooling of the crust during periodic (time span 100 Ma) contraction were possibly the reasons why the thick crust stabilized.

Selected references (tectonic model): Ward (1987), Gaál (1990), Tuisku & Laajoki (1990), Lahtinen (1994), Kohonen (1995), Lahtinen et al. (2005, 2009, 2015b, 2016), Mikkola et al. (2018).

Selected references (crustal-scale data): Hölttä et al. (2000), Kozlovskaya et al. (2004), Yliniemi et al. (2004), Kukkonen et al. (2006), Korja et al. (2006), Sorjonen-Ward (2006), Peltonen & Brügman (2006), Lehtonen & O'Brien (2009), O'Brien & Lehtonen (2012), Vaittinen et al. (2012).

2.2.2.2 Other models for the AP boundary

Hietanen (1975) presented a plate tectonic model with subduction towards the present ENE, and Gaál & Gorbatschev (1987) and Ekdahl (1993) later followed this basic concept with the development of an associated back-arc basin along the craton margin, defining the AP boundary.

Park (1985) proposed a model with exotic terranes juxtaposed along the Archean craton margin along a major strike-slip fault. Kontinen & Paavola (2006) also favoured a strike-slip fault origin for the AP boundary and excluded the occurrence of the Jormua–Outokumpu marginal sea. They considered the stacked structural architecture (thick crust) to be chiefly of Archean origin.

2.2.2.3 Geological AP cross sections

The area of geological cross-section AP 1 is covered by the best deep crustal data set in Finland (Table 1, Fig. 3). Cross-section AP 1a occurs in an area of MT data, but cross-sections AP 1b and AP 1c are class C cross-sections. Cross-section AP 2 coincides with FIRE 3a and 3, interpreted in several publications, and gravity inversion has additionally been carried out (Leväniemi, unpublished data). Cross-section AP 3 utilizes Baltic refraction studies (the interpretation provided by Janik 2010) and a crustal conductance model by Korja et al. (2002). The depth of the rapakivi complex has been taken from Elo & Korja (1993). Earlier studies regarding the Baltic cross-section have also been published (Luosto et al. 1985, 1990, Korhonen et al. 1986), but they have not been utilized in this work. Cross-section AP 3a is a class C cross-section based on geological data. Cross-section AP 1 is presented as an example in Figure 3, and other AP cross-sections are provided in the Appendix 2.

The Karelia Province (lower plate) includes Archean complexes where the combined Lentua and Ilomantsi complexes are considered as the least stretched during Paleoproterozoic rifting. The easternmost reactivated faults are considered to locate the marginal fault. The Pudasjärvi complex appears to have separated as a crustal block with a rifted western margin but a non-stretched eastern margin. Smaller Archean complexes are rifted and strongly attenuated and/or detached blocks of Archean crust formed during prolonged rifting and extension. The sedimentary cover includes all the rocks of the Karelia supergroup and several suites. The amount of intrusive rock and the grade of migmatization increase towards the Archean–Proterozoic boundary.

The Central Finland Province (upper plate) in the AP cross-sections comprises ca. 1.93–1.92 island arc magmatism (Northern Ostrobothnia supergroup) and 1.90–1.87 Ga continental arc magmatism (Central Ostrobothnia supergroup and Central Finland Granitoid Complex). The crustal units in southern parts of cross-sections AP 3 and AP 3b and the northern part of cross-section AP 4 are respectively discussed together with the Svecofennia cross-sections and the Central Lapland cross-sections.

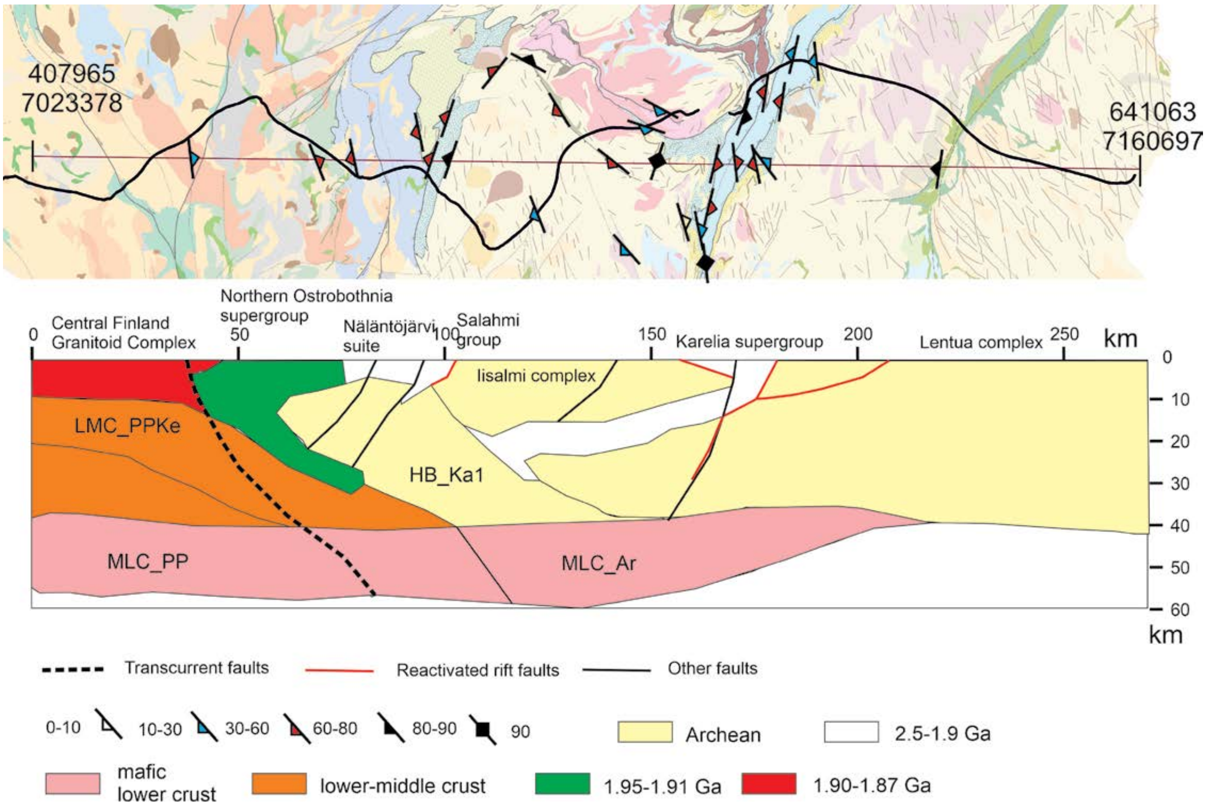

Fig. 3. Geological cross-section AP 1.

Subsurface units:
One important feature in central Finland is an abnormally thick crust along the Archean–Proterozoic boundary correlating with the occurrence of thick high-velocity (mafic) lower crust (e.g., Korsman et al. 1999). It is non-reflective but possibly conductive (Vaittinen et al. 2012). Its composition is granulitic, but eclogitic rocks are possible in small amounts (Kukkonen et al. 2008). In this context, we have divided this mafic lower crust into Archean and Paleoproterozoic parts.

MLC_Ar: Mafic lower crust. Interpreted as a mixture of extended Archean lower crust and magmatic additions from 2.1–2.05 Ga and 1.87 Ga mafic magmatic underplating events (Lahtinen et al. 2016).

HB_Ka1: Hidden Archean block. Originally a similar rifted and attenuated block to the Iisalmi complex.

MLC_PP and LMC_PPKe are discussed in section 7.3.

2.2.3 The Norrbotten–Karelia boundary (NK cross-sections)

2.2.3.1 Tectonic model

The nature of the boundary between the Norrbotten and Karelia tectonic provinces (Kohonen et al. 2021) is still controversial. Possible scenarios for the origin of the boundary are: 1) a suture (a plate boundary or transform fault), 2) an intracontinental rift that subsequently inversed to a thrust and fold belt or 3) an intracontinental strike-slip shear zone. Our tectonic model is based on the assumption that the boundary is a cryptic suture overprinted by a strike-slip deformation zone.

The Karelia continent (lower plate) underwent several Paleoproterozoic rifting stages, and the onset of attenuation of the crust in Lapland appears to have been related to emplacement of the ca. 2.44 Ga layered intrusions followed by several stages of mafic dykes intruding the surrounding supracrustal belts. The bimodal volcanic rocks (2.09–2.05 Ga) at the western margin of the Karelia continent are plume-related EMORB-OIB rocks that mark the final continent breakup. Central Lapland, dominated by the Central Lapland Granitoid Complex, is considered to represent an aulacogen formed during this rifting. The Kittilä oceanic arc-affinity rocks at 2.02 Ga represent an ocean floor and west-directed subduction zone formed west of the Karelia continent.

The compressional tectonic evolution of northern Fennoscandia occurred between 1.93 and 1.76 Ga, when an E–W, locally NW–SE and NE–SW, first compressional phase (D1; 1.93–1.90 Ga) resulted in the at least 600-km-long and in part over 300-km-wide E-vergent Lapland foreland fold and thrust belt (FTB). The collision was initiated with continent (Karelia) – arc (Kittilä) collision and followed by continent (Karelia) – continent (Norrbotten) collision. The Lapland FTB is rather well preserved in the east, but when approaching the boundary in the west the bedrock is multiply deformed (D2–D5) and also records several magmatic events. Heat input is seen in the central part of the Central Lapland granitoid complex, which was near solidus for 100-120 Ma until ca. 1.78 Ga. There was also a change from Barrovian-type metamorphism (D1) to Buchanan-type HT-LP metamorphism (D2–D5) during the complex tectonic evolution. The collisional boundary is at present characterized by syn-D1 to post-D1 sedimentary rocks and a voluminous occurrence of intrusions overprinted by young subvertical to vertical tectonics.

Selected references (tectonic model): Hanski & Huhma (2005), Hölttä et al. (2019), Iljina & Hanski (2005), Köykkä et al. (2019), Lahtinen & Köykkä (2020), Lahtinen et al. (2005, 2009, 2015a,c, 2018), Nironen (2017a,b), Vuollo & Huhma (2005).

Selected references (crustal-scale data): Kukkonen et al. (2006), Korja & Heikkinen (2008), Patison et al. (2006).

2.2.3.2 Other models

We prefer the model with the opening of an ocean west of the Karelia continent. However, another possibility could be that the 2.1–2.05 Ga rifting stage did not lead to an ocean opening but instead it led to a N–S-oriented intracontinental basin or failed rift (Nironen 1997). Nevertheless, this should have been wide enough to accommodate shortening leading to the 300-km-wide Lapland foreland FTB.

Skyttä et al. (2019) proposed that the Archean in northern Fennoscandia is part of one Archean continent that broke up at 2.45 Ga due to NE–SW extension. The proposed Norrbotten–Karelia boundary would be one of the pre-existing Archean structures reactivated as Paleoproterozoic strike-slip zones (see also Berthelsen & Marker 1986a, Kärki et al. 1993). However, the E-vergent Lapland foreland FTB is not compatible with this model.

2.2.3.3 The Geological NK cross–sections

The geological NK cross-sections are typically class C cross-sections (Table 1, Appendix 2), but the NK 1 cross-section (Fig. 4) partly follows FIRE 4B and NK 2 occurs close to FIRE 4. In addition, we have used the 3D upper crust models of Niiranen et al. (2014a) in sketching. All the cross-sections have been sketched across the national border with Sweden.

The Karelia province (lower plate) along the NK cross-sections includes the Pudasjärvi complex and several Archean complexes as inliers/windows. The largest of these is the Hetta complex. The sedimentary cover includes all the rocks of the Karelia supergroup and several suites. The amount of intrusive rock and the grade of migmatization increase both towards the Norrbotten–Karelia boundary and into the central axial part of the aulacogen, the Central Lapland Granite Complex.

The Vesmajärvi rocks of the Kittilä suite are considered to represent allochthonous arc rocks thrust towards the east on the lower plate. The Uusivirka suite (syn-late D1) and Kumpu (Hauki in Sweden) group rocks (syn-D2/D3) are combined and they occur on both sides of the collision boundary. The Olostunturi suite is included in the 1.91–1.87 Ga group based on unpublished detrital zircon data from the Salvastunturi paragneiss (Lauri et al. unpublished data).

The Norrbotten has been divided into the Archean and its cover, and Kiruna-type rocks. The latter includes the Råneå, Porphyrite and Kiirunavaara group supracrustal rocks, as well as Maattavaara and Hauki quartzites (Bergman & Weihed 2020). Intrusive rocks are not separated and are included as part of the Kiruna-type rocks.

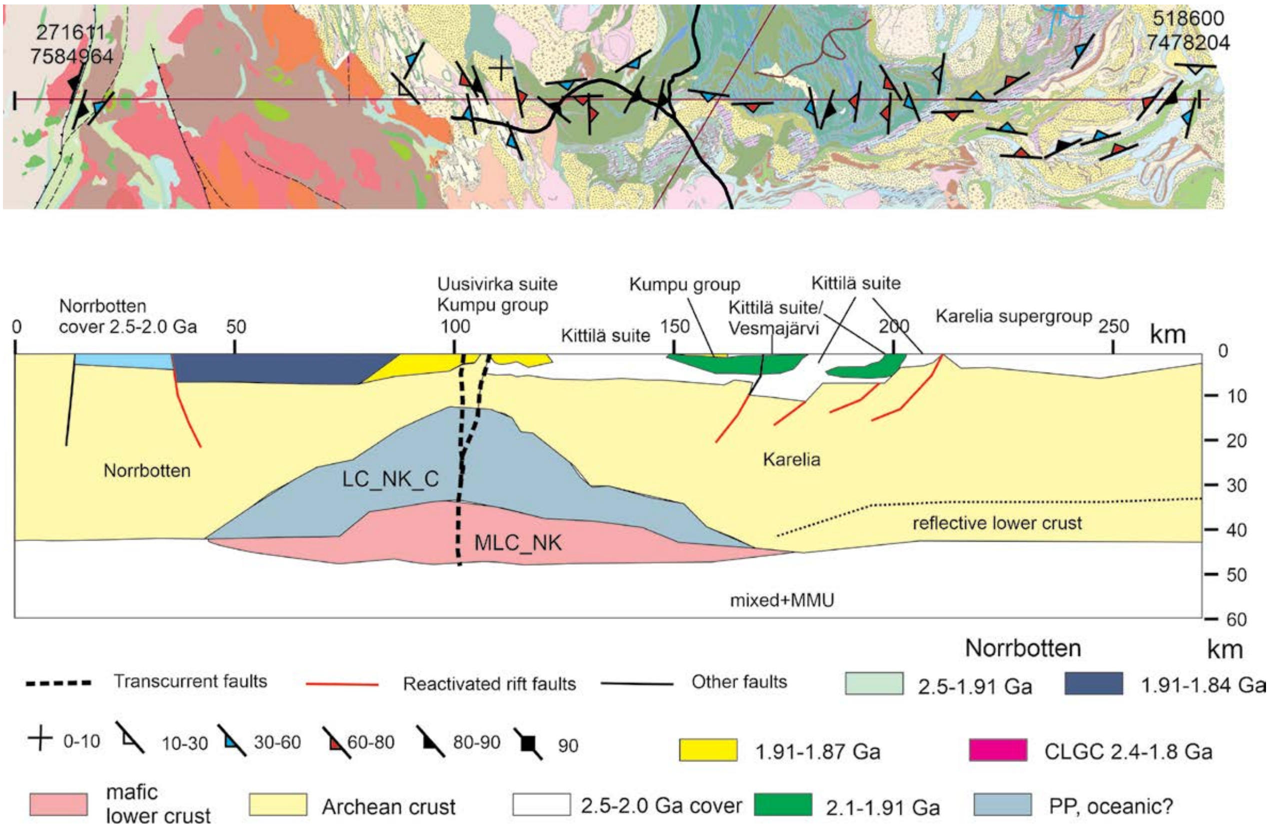

Fig. 4. Geological cross-section NK1.

Subsurface units:

MLC_NK: Mixed crustal units with magmatic underplating, especially at 1.9–1.8 Ga.

LC_NK_C: Inferred underplated material. Possibly mainly Paleoproterozoic "oceanic".

2.2.4. The Kola–Karelia boundary (KK cross-sections)

2.2.4.1 Tectonic model

Here, we follow the tectonic model presented by Lahtinen & Huhma (2019). The collisional foreland in the NE (lower plate), outside Finland, comprises the Kola Province with Archean crust, Paleoproterozoic cover rocks and allochthonous upper plate rocks. The upper plate comprises the Karelia Province with Archean crust, Paleoproterozoic cover rocks and the juvenile Inari arc. The arc hinterland is composed of a retro-arc basin, presently the Lapland granulite complex (LGC) and Umba (UGB) granulite belts. The retro-arc foreland in the SW comprises thrust cover rocks SW of the LGC and the Archean Belomorian belt.

The tectonic model envisages subduction towards the present SW (Inari arc), starting at ca. 1.98 Ga. Underplating of a mid-ocean ridge caused flat subduction and magmatic flare-up at 1.92 Ga over a broad region in the deepening retro-arc basin. During collision (D1) at 1915–1910 Ma, large thrust nappes formed on the foreland and subduction of the lower plate produced eclogites. Collisional shortening in the retro-arc basin (LGC) is seen as recumbent folding and shearing.

Renewed shortening (D2), due to far-field effects in the SW at 1.87–1.86 Ga, caused large-scale crustal duplexing of already cooled granulites towards the retro-arc foreland and inclined upright folding in the opposite direction in the NE part of the LGB and the Inari arc. A switch in the stress field from NE–SW (D2) to NNW–SSE (D3) led to orogen-parallel contraction and buckling. Buckling is seen in the bending of pre-orocline fabrics and the widespread occurrence of gentle-open to close D3 folds, orthogonal to the D1–D2 fabrics, followed by abundant radial fractures during ductile to brittle transition. The end result is a mega-scale multi-layer parallel fold composed of the Inari arc, the retro-arc basin and possibly also the heated retro-arc foreland.

Selected references (tectonic model): Berthelsen & Marker (1986b), Lahtinen & Huhma (2019), Lahtinen et al. (2005), Mints et al. (2007).

Selected references (crustal-scale data): Gaál et al. (1989), Sharov (1997), Kukkonen et al. (2006), Patison et al. (2006), Janik et al. (2009), Niiranen et al. (2014b).

2.2.4.2 Other models

An opposite subduction direction towards the present NE under the LGC has been proposed by Barbey et al. (1984), Tuisku et al. (2006, 2012) and Nironen (2017b). Daly et al. (2006) proposed a model of two opposite subduction systems within the closure of the Pechenga–Varzuga and Lapland–Kola oceans.

The curvature of the LGC has previously been considered to have formed coeval with thrusting (e.g., Gaál et al. 1989, Daly et al. 2006) consistent with the bend being a progressive orocline and not a secondary orocline, as proposed by Lahtinen & Huhma (2019).

2.2.4.3 Geological KK cross–sections

There are three cross-sections, of which cross-section KK 1 is a class A cross-section and cross-section KK 1a a class C cross-section (Table 1, Appendix 2). Cross-section KK 2 utilizes the EGG1 reflection cross-section (Fig. 1), which has been interpreted down to 18 km depth (Sharov 1997).

Lower plate rocks (Kola province) are not found in Finland at the surface, but the inferred suture (Fig. 5) dips below the Karelia province rocks. The upper plate (Karelia province) includes the Archean Inarijärvi complex and its cover rocks, e.g., the Opuskajärvi group. The arc-related Paleoproterozoic rocks at the surface comprise the Silisjoki and Luossavari suites, Kaamanen complex and Lapland granulite complex. Note that the Lapland granulite complex has been considered as part of the arc system. The Vuotso complex includes SW thrust cover rocks.

2.2.5. Central Lapland (CL cross-sections)

2.2.5.1 Tectonic model

See also section 2.2.3.1 for the NK tectonic model. In the first collisional stage (D1), east-vergent thrusting and stacking at 1.92–1.90 Ga thickened the crust and led to the onset of Barrovian-type metamorphism. Subsequent orthogonal N–S shortening (D2) further thickened the crust and maintained most of the Central Lapland granitoid complex (CLGC) under compression, leading to hot thickened crust at 1.88 Ga. The easternmost peripheral part of the E-vergent Lapland foreland fold and thrust belt (CL 2) is only slightly affected by the

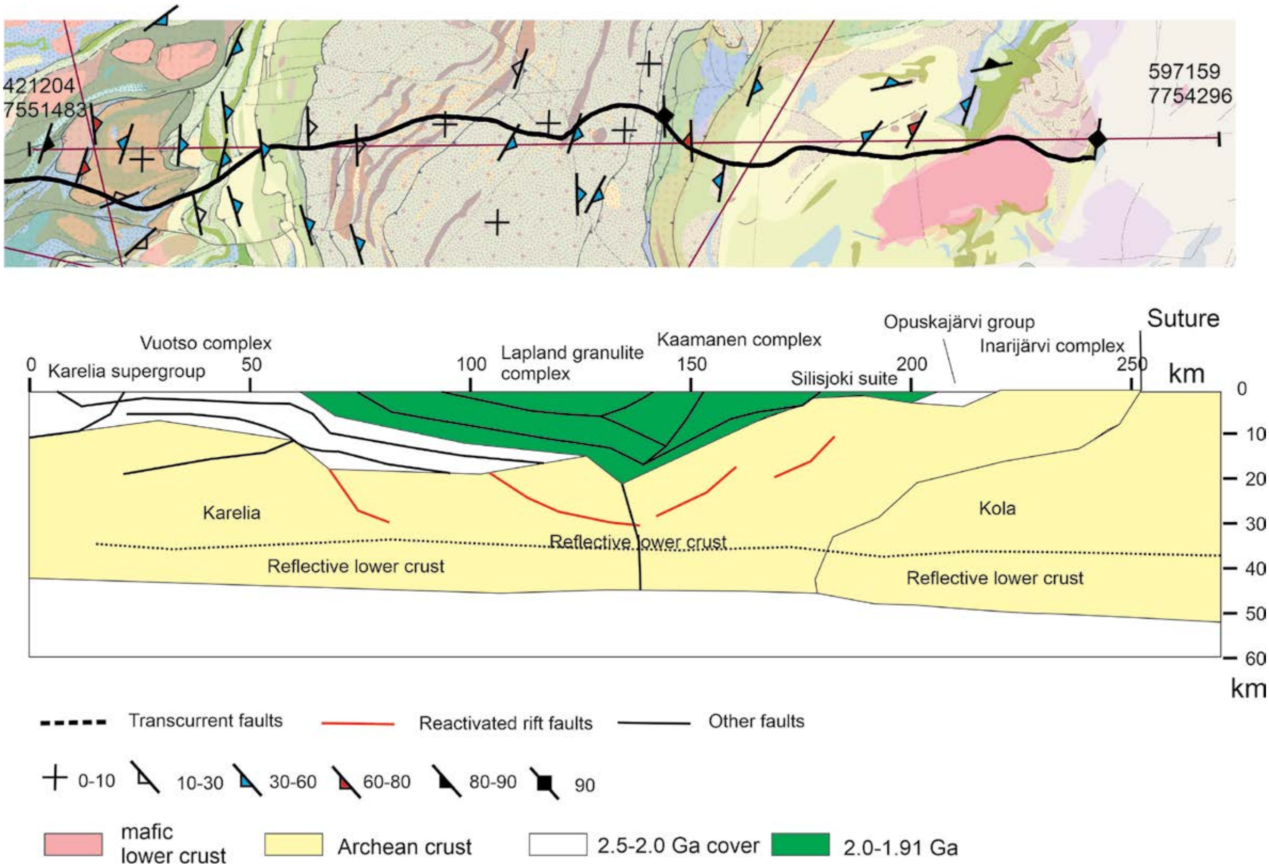

Fig. 5. Geological cross-section KK 1.

later deformation events, but in the stretched part of the Archean basement, the earlier rift structures, especially in the aulacogen (CLGC), have facilitated the N–S shortening and E–W-oriented D2 structures dominate the map pattern (CL 1). The D3 is related to a major SW–NE compressional event in the Svecofennian province, and far field effects are especially seen in the 1.89–1.86 Ga magmatic and supracrustal rocks.

After prolonged heating, the Archean basement started to act in a ductile manner and long-wavelength crustal-scale D4 folds occurred, seen as domal structures in the aulacogen (CLGC) and more to the east as a major D4 anticlinorium (wavelength 70–100 km), explaining the metamorphic zonation from greenschist facies in the south to medium pressure amphibolite facies in the north. In the following extensional stage, mantle-derived magmas intruded along the cryptic suture and large volumes of granites, formed due to decompression melting, intruded the CLGC.

Selected references (tectonic model): Lahtinen et al. (2018), Köykkä et al. (2019), Lahtinen & Köykkä (2020), Hölttä et al. (2019), Silvennoinen (1972, 1991).

Selected references (crustal-scale data): Kukkonen et al. (2006), Korja & Heikkinen (2008), Patison et al. (2006), Silvennoinen et al. (2010), Tiira et al. (2014).

2.2.5.2 Other models

Gaál et al. (1989) suggested that during the later stages of its structural development, the northern part of the CLGC was influenced by diapiric intrusion of ca. 1.8 Ga granites. Kärki et al. (1993) proposed, in their shield-wide shear-zone model, that tectonic underplating possibly occurred in the CLGC during their D3 (D2 of Lahtinen et al. 2018). Tiira et al. (2014) proposed a 2.44 Ga mantle plume (seen as layered intrusions) initiated triple junction with a focal point at the intersection of the CLGC and the Pudasjärvi and Lentua complexes followed by tectonic spreading in a NW–SE direction. This model has similarities to that proposed by Skyttä et al. (2019), but with an orthogonal spreading direction.

2.2.5.3 Geological CL cross-sections

There are two class B cross-sections where CL 1 follows the FIRE 4 reflection cross-section and CL 2 follows the Hukka 2007 refraction cross-section (Table 1, Appendix 2). In the CL1 cross-section (Fig. 6), the upper crustal high-density body (Silvennoinen et al. 2010) has been included as part of the CLGC. The poorly reflective lower crust probably indicates a mixture of granulitic rocks and magmatic additions during 2.44–1.8 Ga magmatic events.

The central part of the CL 2 cross-section is interpreted as almost non-stretched, whereas small

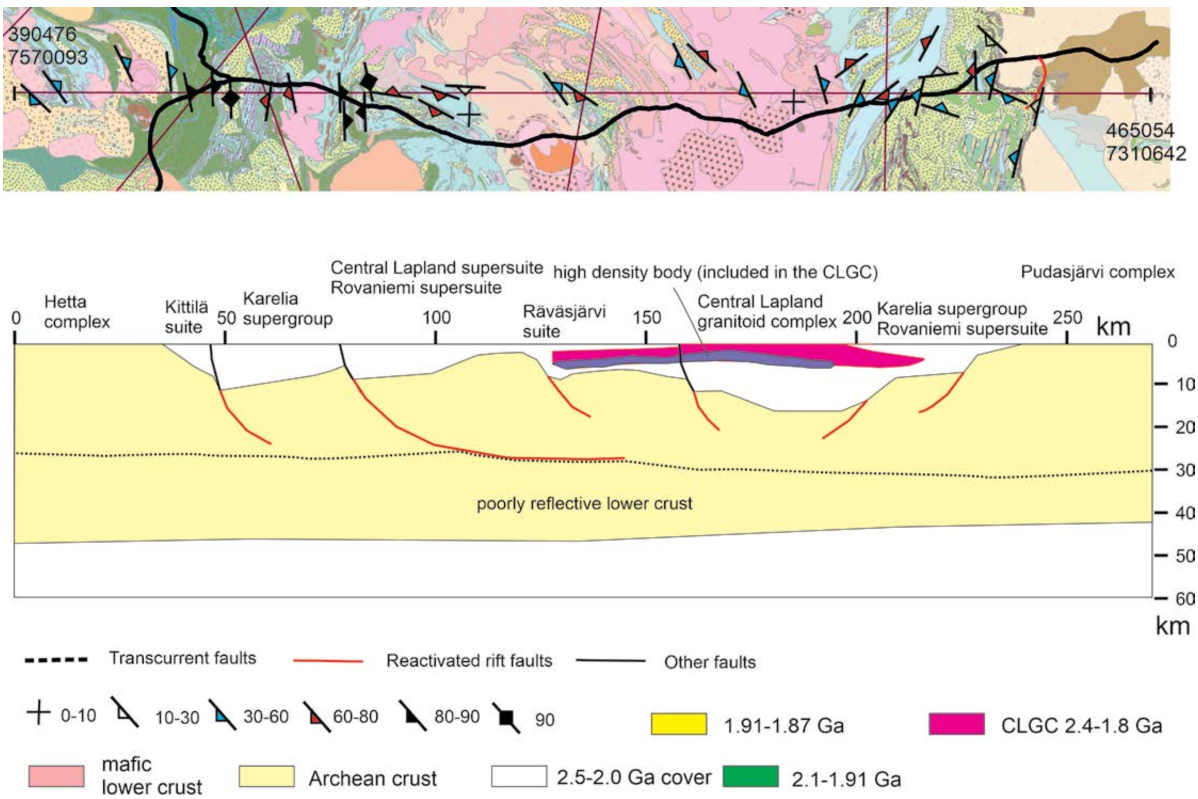

Fig. 6. Geological cross-section CL 1.

rift basins have formed in the south and north. The long-wavelength major D4 anticlinorium is seen as a bulge in the lower crust (see Fig. 11 in Tiira et al. 2014). In this model, the Suomujärvi complex, the Archean crust below CL 2 and the northern boundary of the aulacogen (CLGC) are a continuation of the Lentua complex, whereas the Archean crust below the southern and central parts of the aulacogen relate to the Pudasjärvi complex.

2.2.6. Svecofennia (SV cross-sections)

2.2.6.1 Tectonic model

The tectonic model for Svecofennia starts with the AP boundary tectonic model, with continent (arc) – arc/microcontinent collision at ca. 1.91 Ga (see 2.2.2.1), followed by a reversal of subduction and voluminous subduction-related arc magmatism at 1.90–1.88 Ga. This event is seen in an anomalous peak of U–Pb ages (Huhma et al. 2011) from igneous rocks widely found at the present exhumation level in Finland. Another conspicuous feature in central Finland is the folded architecture of the crustal-scale conductance anomaly (Korja et al. 2002). Here, we follow the concept of Bothnian coupled oroclines and their continuation to southern Finland (see Lahtinen et al. 2014, 2017, Chopin et al. 2020) resulting from the buckling of the linear accretionary system due to dextral transpression along the Karelian continental margin. We interpret that the originally linear, NW-striking geometry restores the lithological belts, conductance anomaly, metamorphic zones and structural vergences to a common direction. This indicates that the orogen consists of a SW-facing arc (1.90–1.88 Ga) that shortened along NE-verging folds and thrust faults at ca. 1.88 Ga, followed by oroclinal buckling at ca. 1.87 Ga. Thus, we favour the model with one linear arc system (Fig. 15a in Lahtinen et al. 2017) for the Svecofennia area, but the sketched SV cross-sections also fit the model with double-plunging subduction zones (Fig. 15b, ibid.).

An association of paleosol and ultramature quartzites (≤1.87 Ga) in southern Finland marks a major nonconformity, which was followed by a rifting period at 1.85–1.83 Ga (Lahtinen & Nironen 2010, Nironen & Mänttäri 2012). Basin inversion and strong NW–SE shortening occurred in southern Finland at ca. 1.83–1.82 Ga (Ehlers et al. 1993, Väisänen & Hölttä 1999, Pajunen et al. 2008, Skyttä & Mänttäri 2008, Saalmann et al. 2009, Nironen & Mänttäri 2012). This time period was an important crustal reworking stage and is separated as the crustal Southern Svecofennia Subprovince (Kohonen et al. 2021). The tectono-metamorphic activity continued until ca. 1.78 Ga, seen in young monazite ages (Hölttä et al. 2019).

Selected references (tectonic model): Lahtinen et al. (2014, 2017), Chopin et al. (2020).

Selected references (crustal-scale data): Korja et al. (2002), Korja & Heikkinen (2005, 2008), Korja et al. (2009), Kukkonen et al. (2006), Lahtinen et al. (2009), Sorjonen–Ward et al. (2006).

2.2.6.2 Other models

The traditional accretionary model for the Paleoproterozoic Svecofennia in Finland implies several subduction zones, accretionary prisms and microcontinents (e.g., Lahtinen et al. 2005, 2009, Korja et al. 2006, Nironen 2017a). In this model, nearly contemporaneous arc magmatism is caused by double-plunging subduction zones. This model has also been adapted in the tectonic province division into the Central Finland and Southwestern Finland Provinces (Kohonen et al. 2021).

Pajunen et al. (2008) proposed a clockwise rotation of crustal blocks at 1.87 Ga causing a sigmoidal pattern within the Central Finland granitoid complex (CFGC) to explain the bending seen in the southern Bothnian orocline. Saalmann et al. (2009) favoured a tectonic switching and SW accretion model. A core complex model with gravitational spreading at about the same time as the proposed buckling (1.87–1.86 Ga) has been proposed for the evolution of the CFGC (Korja et al. 2009, Nikkilä et al. 2015).

2.2.6.3 Geological SV cross-sections

Altogether, there are 12 cross-sections, of which cross-section SV 2 is a class A cross-section and cross-sections SV1, SV3 and SV4 are class B cross-sections (Table 1, Appendix 2).

The Central Finland Province close to the AP boundary comprises ca. 1.93–1.92 Ga island arc magmatism (Northern Ostrobothnia supergroup) formed prior to the ca. 1.91 Ga collision. The 1.95–1.91 Ga rocks in cross-section SV 1 (Fig. 7) include rocks of the Lappfors, Lapua and Pirttikylä suites with a proposed extrusion and depositional age of ca. 1.91–1.92 Ga, or even earlier, and they are thus pre-syn-late in relation to the ca. 1.91 Ga collision. The 1.92 Ga Veteli tonalite and some volcanic rocks in this area have been correlated with the ca. 1.93–1.92 Ga arc rocks in the Northern Ostrobothnia supergroup (Lahtinen et al. 2017). Thus, it appears that this package of suites possibly includes rocks of different ages. Nevertheless, they are older than and partly form the basement for the 1.90–1.87 Ga continental arc magmatism (Central Ostrobothnia supergroup, Central Finland Granitoid Complex, Jurva suite).

The Vaasa complex has a migmatitic rim (diatexites and metatexites) and a 1.88–1.87 Ga *in situ*-formed granitic core composed of several subdomes (e.g., Chopin et al. 2020). The maximum sedimentation age of the supracrustal precursors of the Vaasa complex is 1.92 Ga (Kotilainen et al. 2015), and thus similar to ages found in the surrounding sedimentary rocks.

The Pirkanmaa migmatite suite and the Renkajärvi suite are correlated with the Lapua and Pirttikylä suites and represent the pre-arc rocks (Fig. 8). The Häme migmatite suite has been divided into two groups, where some parts are correlated with the Pirkanmaa migmatite suite and other parts are grouped with the 1.90–1.87 Ga arc rocks. The Southern Finland granite suite and associated migmatites and the Tiirismaa suite quartzites and related rocks are considered as their own group of rocks formed above and after the nonconformity.

Rapakivi granites and younger formations are considered if they are large enough at the scale of the 3D crustal model.

The LMC_PPKe crustal-scale thick-skin stacking is related to the second collision stage at ca. 1885 Ma due to NE–SW shortening. The younger stacking (orocline faults), especially characterizing the upper crust, is due to NW–SE shortening (Sorjonen-Ward 2006, Lahtinen et al. 2016) and is interpreted to have formed during oroclinal buckling at ca. 1.87 Ga.

Subsurface units:

MLC_PP: Interpreted as a mixture of extended Paleoproterozoic lower crust (ca. 2.1–2.0 Ga) and magmatic additions from 2.0–1.87 Ga mafic magmatic underplates. Also referred to as the Keitele micrcontinent under the CLGC (e.g., Lahtinen et al. 2005, Korja & Heikkinen 2008) composed of granulitic crust. Typically non- to moderately reflective due to homogenization by the magmatic underplating.

LMC_PPKe: Paleoproterozoic lower-middle crust under the CLGC showing thick-skin stacking during collision (Sorjonen-Ward 2006, Lahtinen et al. 2016). We correlate this W–SW-vergent stacking with the collisional deformation event at ca. 1.885 Ga.

LMC_PPBo: Lower-middle crust of a microcontinent (Bothnia mc by Lahtinen et al. 2005), showing variable reflectivity. Age unknown but could be either Paleoproterozoic and/or Archean.

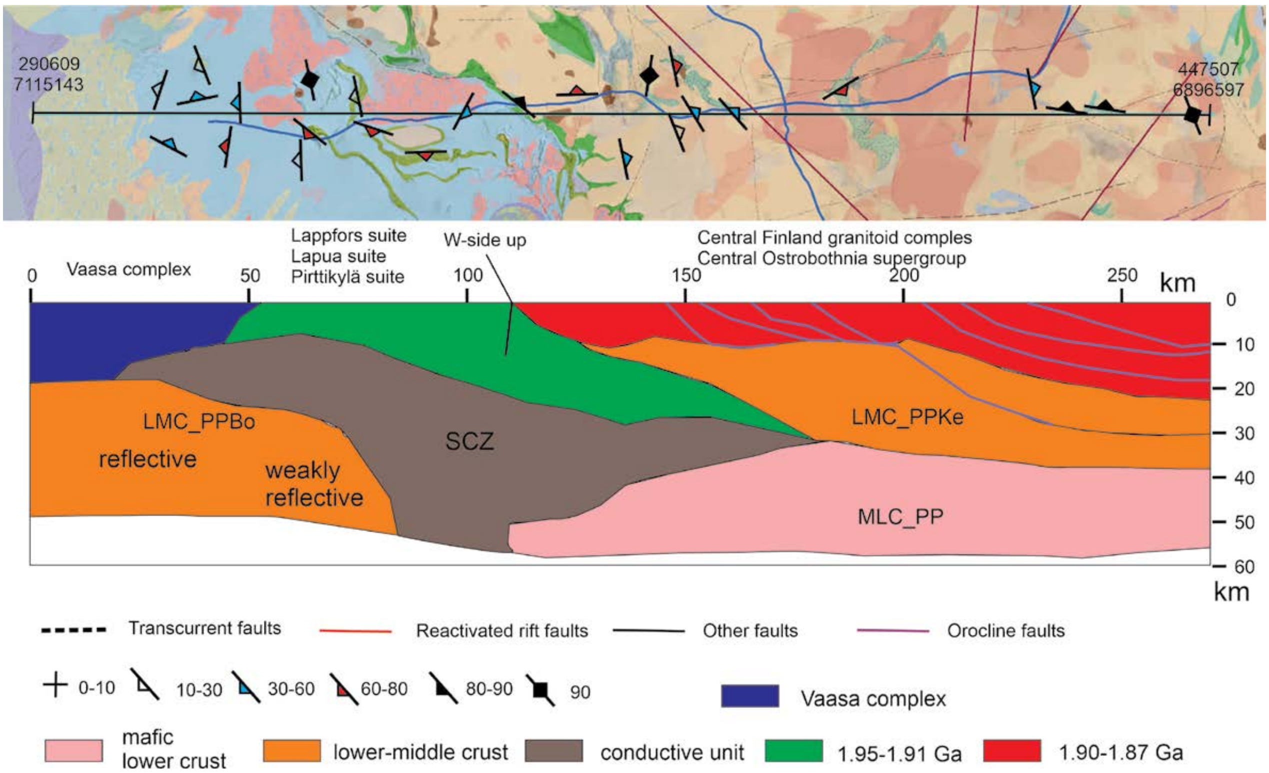

Fig.7. Geological cross-section SV 1.

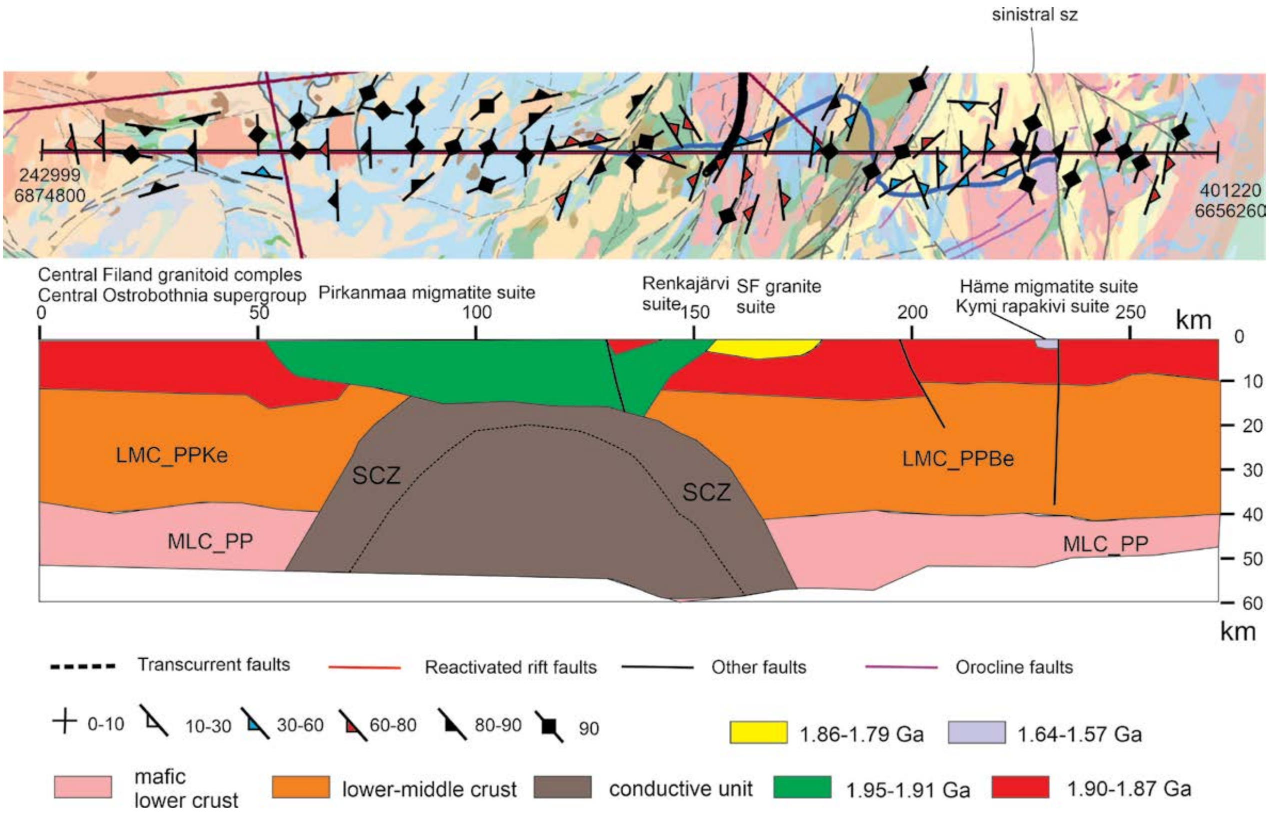

Fig. 8. Geological cross-section SV 3.

LMC_PPBe: Paleoproterozoic lower-middle crust of a microcontinent (Bergslagen mc by Lahtinen et al. 2005).

SCZ: Subduction-collision zone where the upper surface is defined by a crustal-scale conductance anomaly (Korja et al. 2002), while the deep conductors are more likely thin and compact layers with high conductivity (graphitic black schists) rather than thick layers with lower conductivity values (see discussion in Chopin et al. 2020). These units could have derived from the accretionary wedge Pirttikylä suite graphite schists (upper plate) and/or they could represent graphite-rich sediments from marginal basins deposited on the rifted margin of the Bothnian continent (lower plate). The latter model is favoured here. We have interpreted the SCZ in the Pirkanmaa belt (Fig. 8) as a SCZ folded to double-plunging system, also seen in double-plunging upper mantle reflectors (Korja & Heikkinen 2008).

3 3D CRUSTAL GEOLOGICAL MODEL

Because of the lack of direct observations, the 3D crustal geological model above the Moho (Grad et al. 2009) is conceptually mainly based on indirect information. In this chapter, the 3D crustal geological model is constructed using the geological cross-sections presented in this report based on reflection and refraction seismic data, potential field data and earlier available interpretations. The general workflow for the 3D modelling process is presented in Figure 9.

The geological cross-sections based on many different data sets (class A and partly B) are visualized in Figure 10 as a fence diagram using Emerson GOCAD software. In addition, the 3D geological model presented in Figure 11 was constructed using Intrepid GeoModeller, and is based on the implicit approach using co-kriging interpolation (Lajaunie et al. 1997). The 3D model displays the main lithological layers based on the conceptual model used for the cross-section interpretations presented in this report. The model can be easily updated as new data become available or by introducing new conceptual ideas. The main drawback with implicit 3D modelling methods is the loss of details that can be modelled using explicit modelling, but updating is time consuming. Different 3D modelling tools will be compared and large discontinuities will also be included in the crustal model in a later report (Laine in prep.).

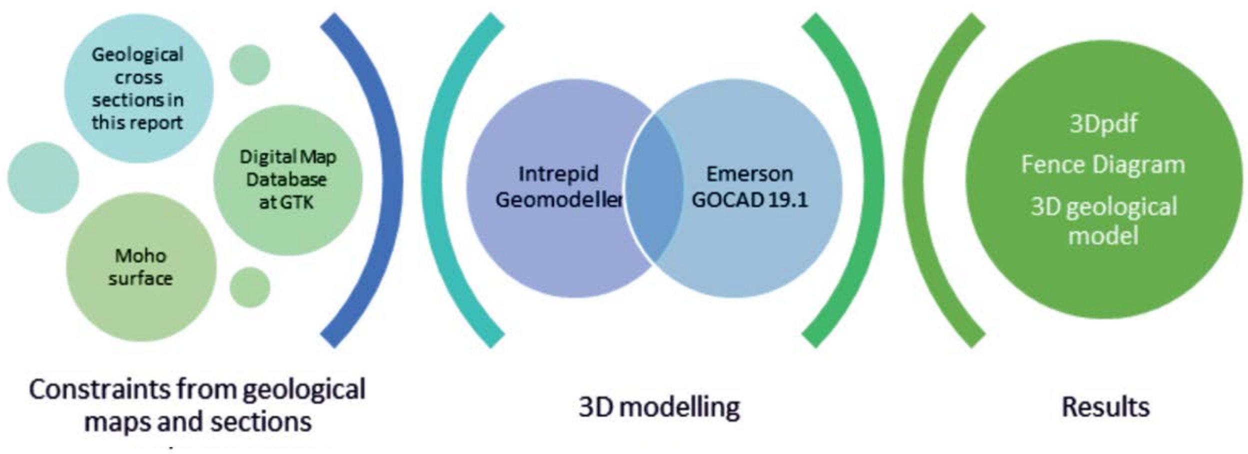

Fig. 9. 3D modelling workflow

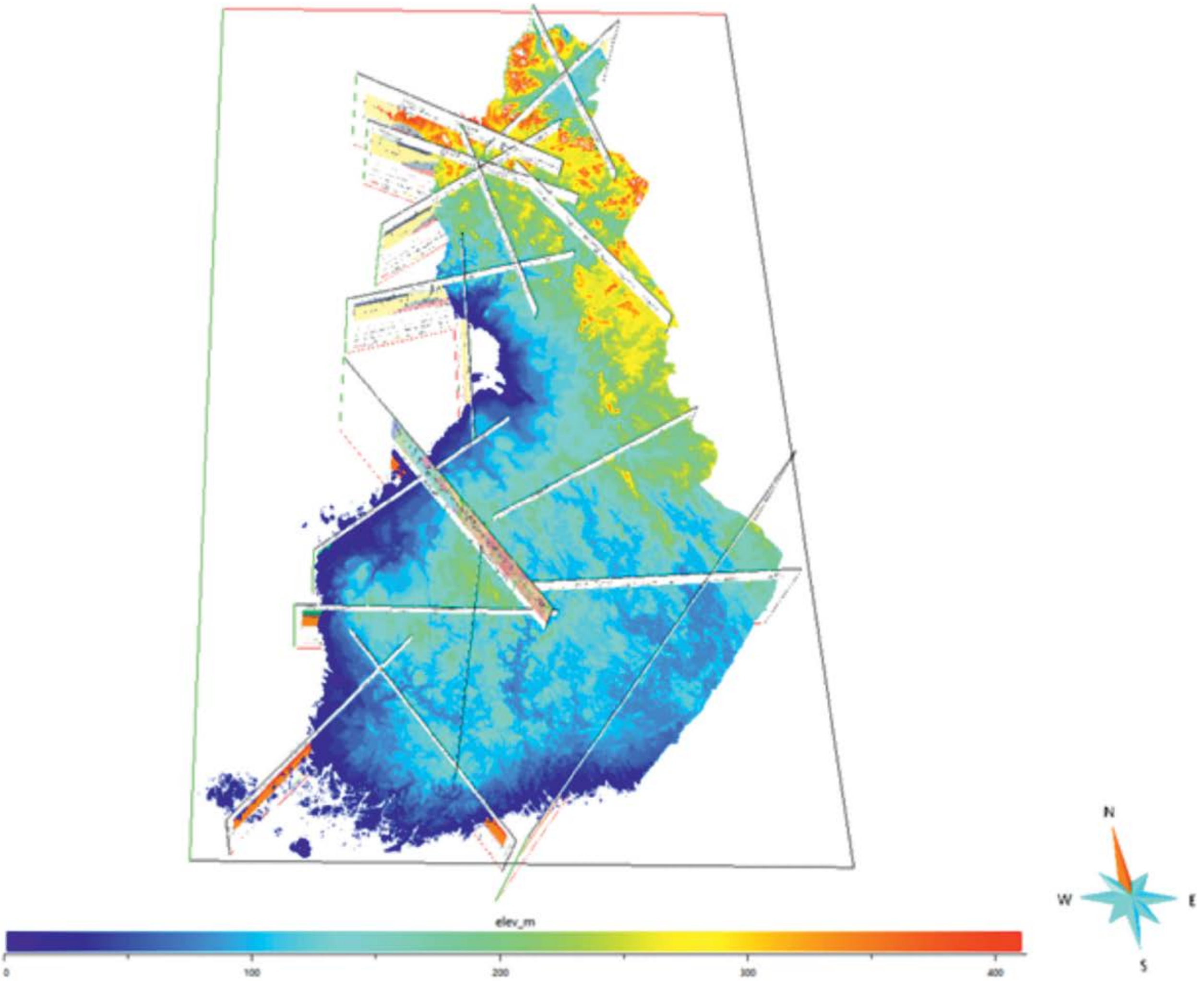

Fig. 10. A fence diagram produced in Emerson GOCAD showing the type A cross-sections based on reflection and refraction seismic data and available interpretations together with the elevation model.

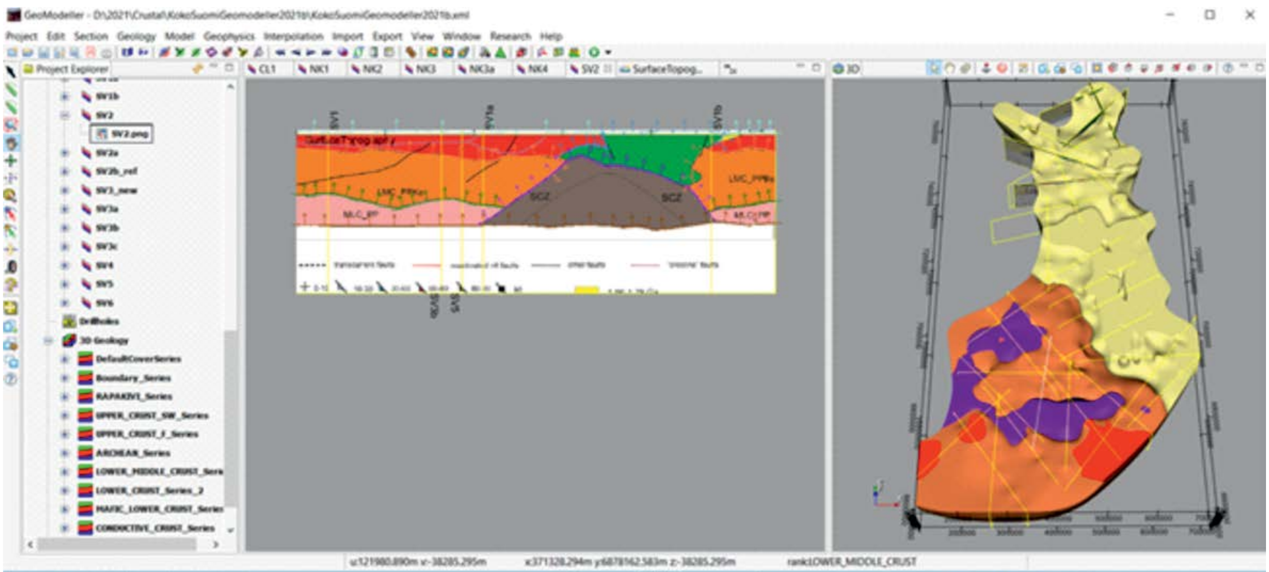

Fig. 11. The GeoModeller modelling window. Cross-section SV2 (Appendix 2) is presented as an example.

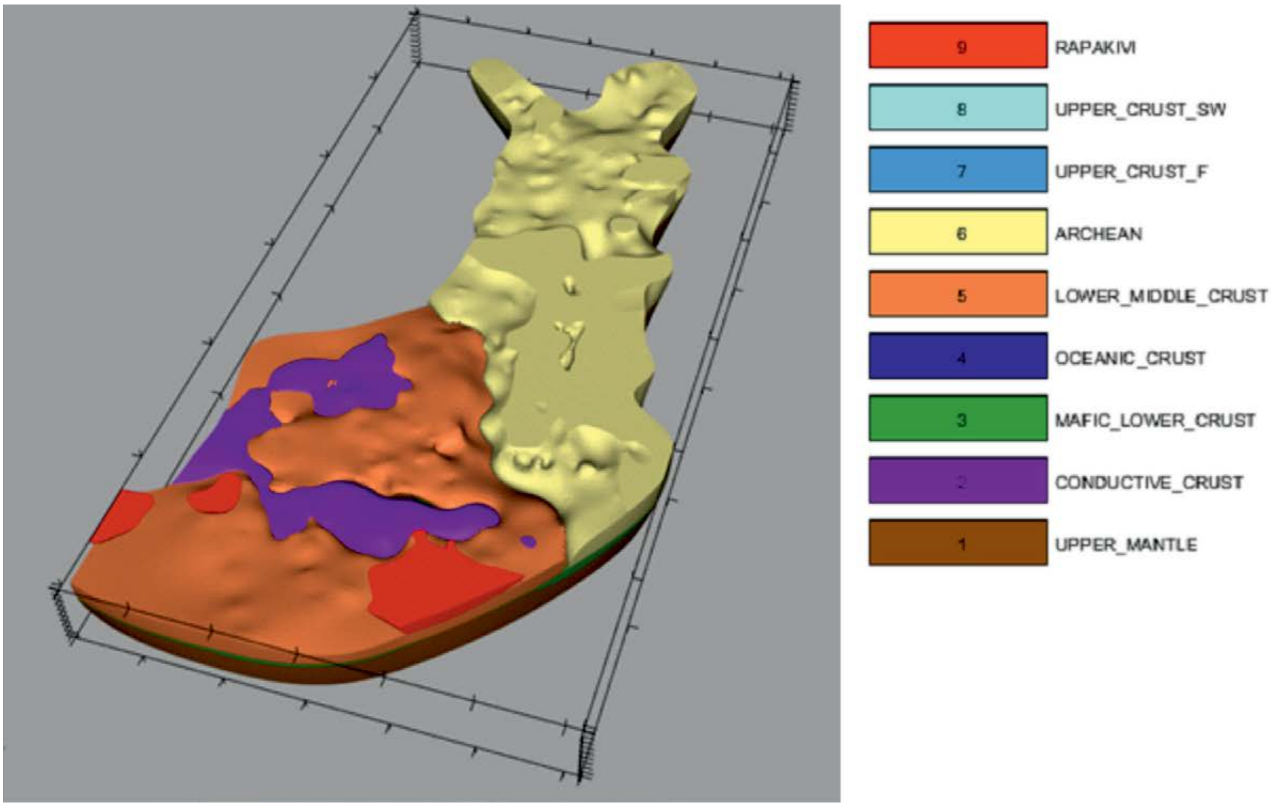

Fig. 12. An example of the 3D crustal geological model (Appendix 1: 3D crustal model (Crustal3D_version1.0.pdf)). Note that the upper crust, apart from rapakivi granites, in the Svecofennian domain and the Paleoproterozoic supracrustal and igneous cover rocks in the Archean domain are not shown.

4 SUMMARY

Here, we present sketched geological 2D cross-sections and a 3D crustal model of Finland. The cross-sections are grouped into five main groups (Fig. 2): 1) the Archean–Proterozoic boundary (AP), 2) the Norrbotten–Karelia boundary (NK), 3) the Kola–Karelia boundary (KK), 4) Central Lapland (CL) and 5) Svecofennia (SV). The sketching is based on surface data, available deep subsurface data and conceptual tectonic models for the groupings. We have used the crustal unit concept, which describes an informal crustal-scale geological unit. The tectonic models used are predominantly interpretations by the first author and to some extent are therefore biased. On the other hand, this is a "harmonized" approach and consistent throughout the process.

Future challenges include the creation of the 3D deep data environment with all the existing available data as raw and interpreted data sets.

Selected cross-sections are presented as a fence diagram and as digitized lines using simplified crustal units. GeoModeller was used to create a 3D crustal model based on simplified versions of the cross-sections. A 3D model should fit the observed data and change accordingly. Tectonic models can change or there might be modifications to the model used, and other 3D models with different approaches should therefore also be tested. Nevertheless, any 3D crustal model should be easily iterated if the basics for the tectonic model change or if new data and interpretations become available.

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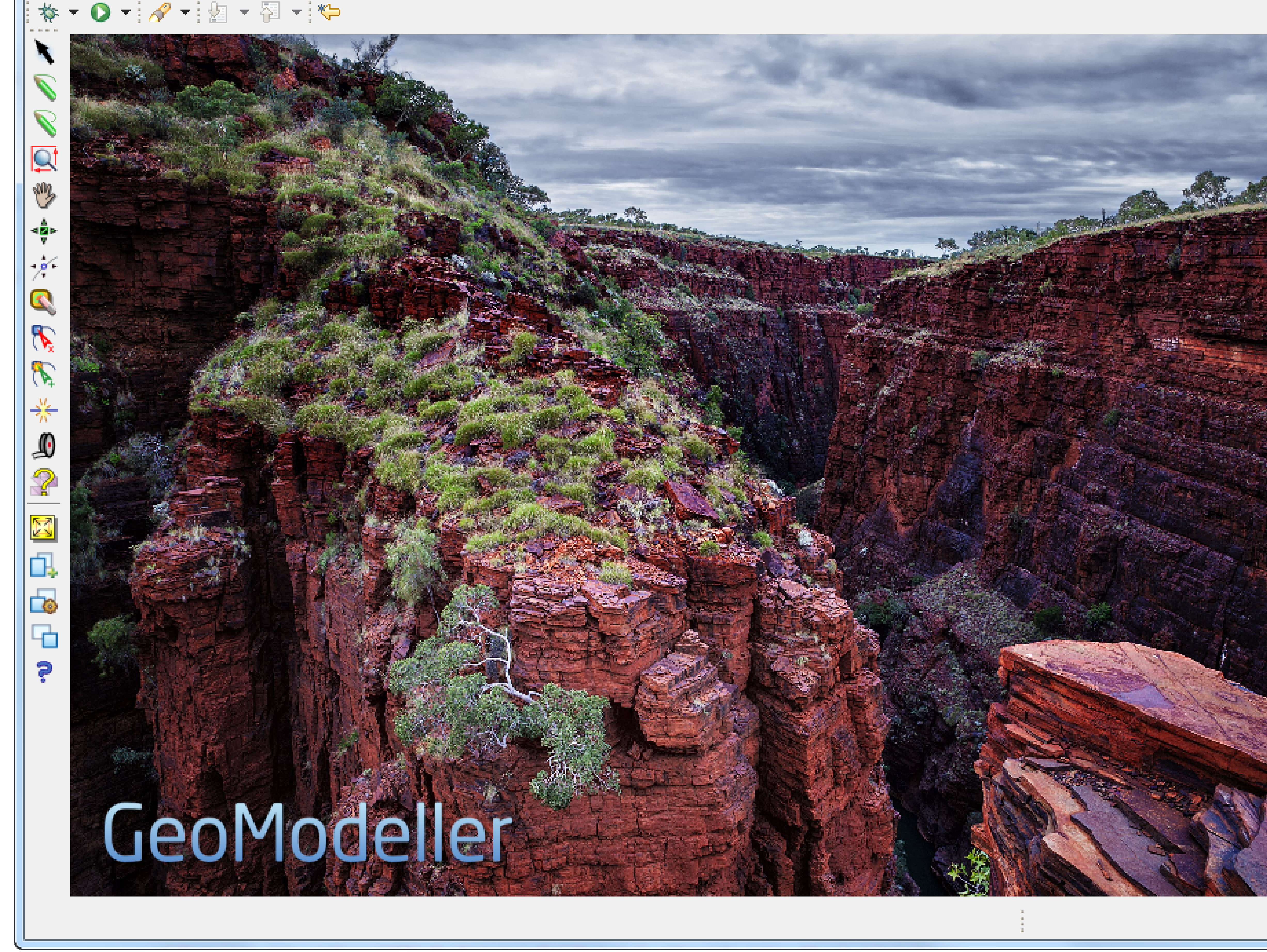

GeoModeller

Appendix 2: Geological conceptual 2D cross sections

Cross sections grouped into five main groups: 1) Archean-Proterozoic boundary (AP); 2) Norrbotten-Karelia boundary (NK); 3) Kola-Karelia boundary (KK); 4) Central Lapland (CL); 5) Svecofennia (SV).

All lines

AP 1_AP1a

AP 1b_AP 1c

AP 2

AP 3_AP3a

AP 4

NK 1_NK 2

NK 3_NK 3a

NK 4

KK 1_KK 1a

KK 2

CL 1_CL 2

SV 1_SV 1a

SV 1b

SV 2_SV2a

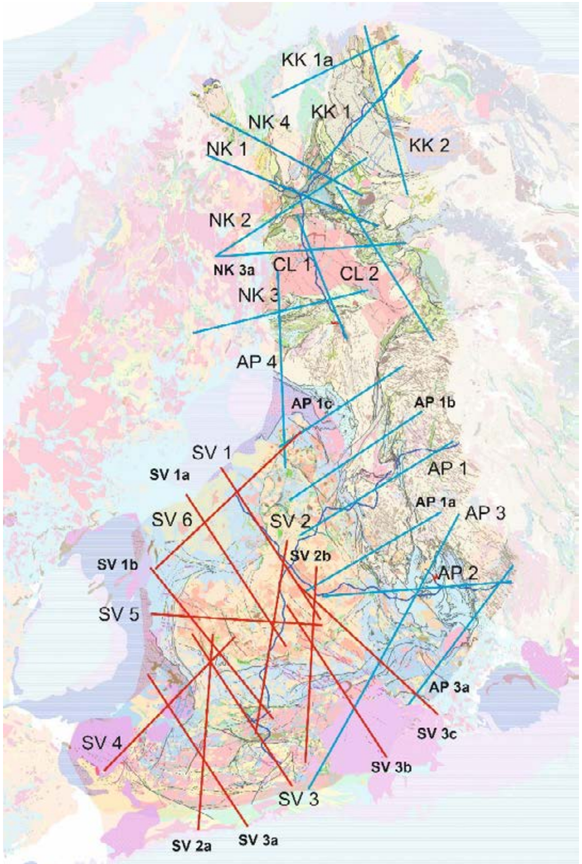
SV 2b

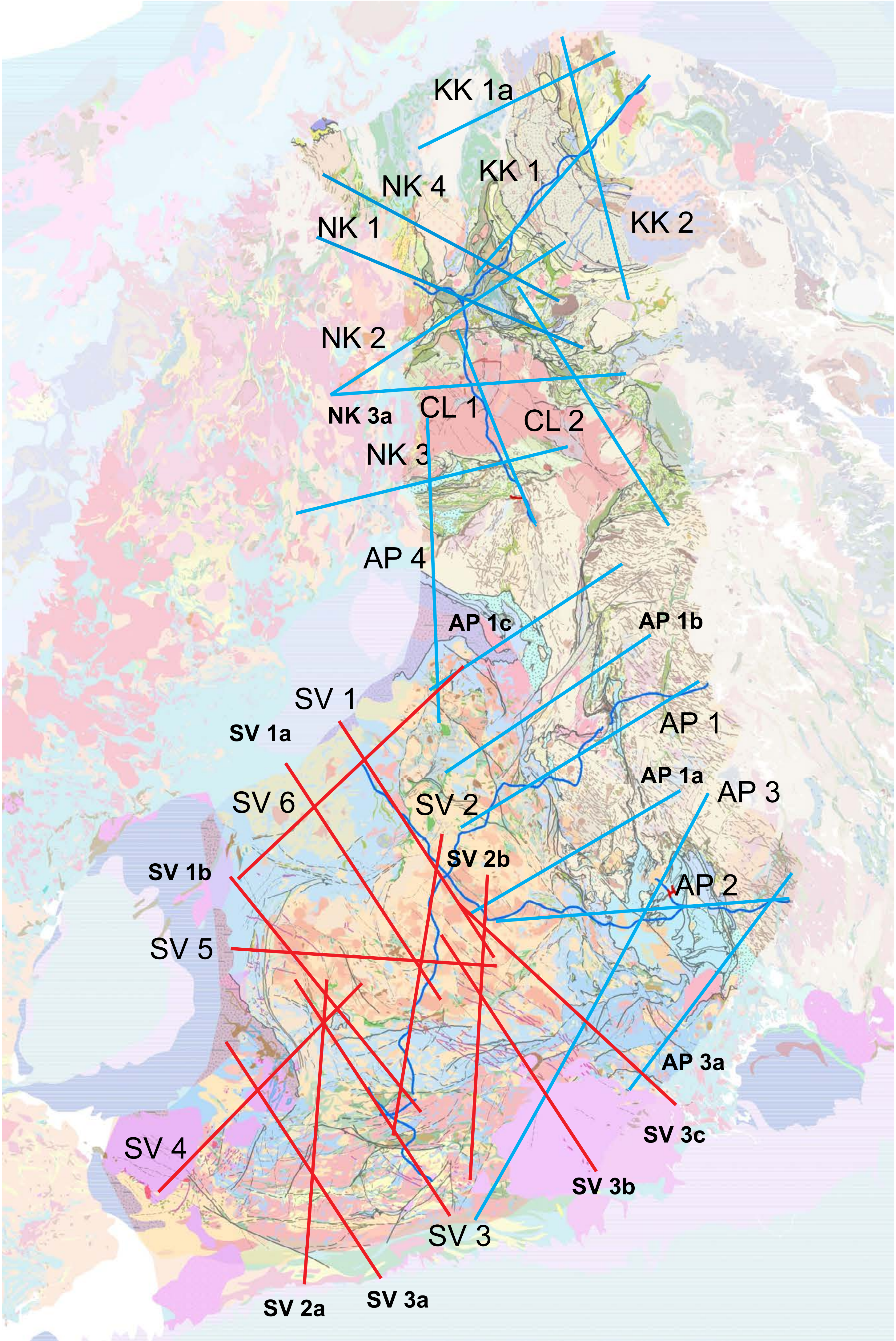
SV 3_SV 3a

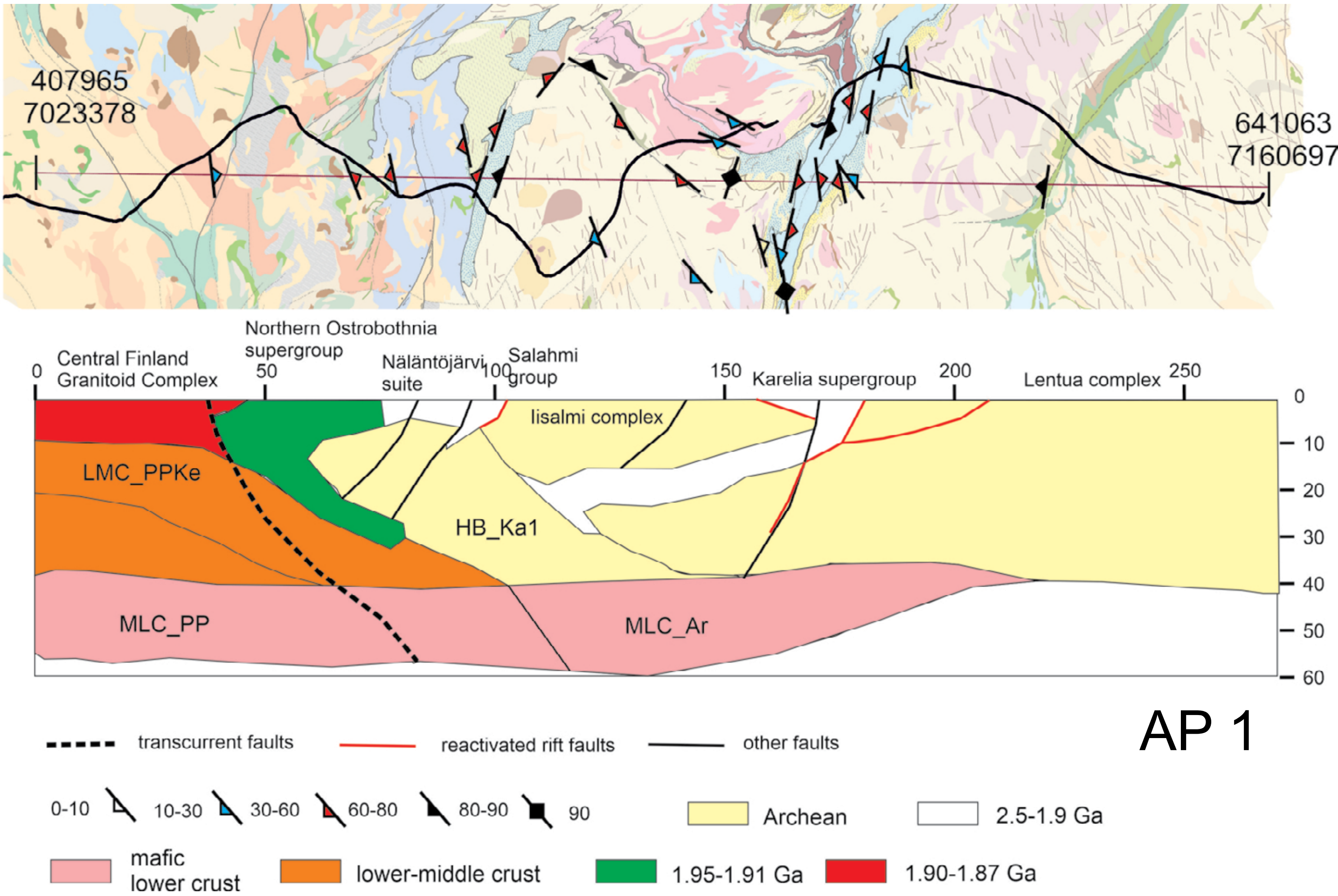
SV 3b_SV 3c

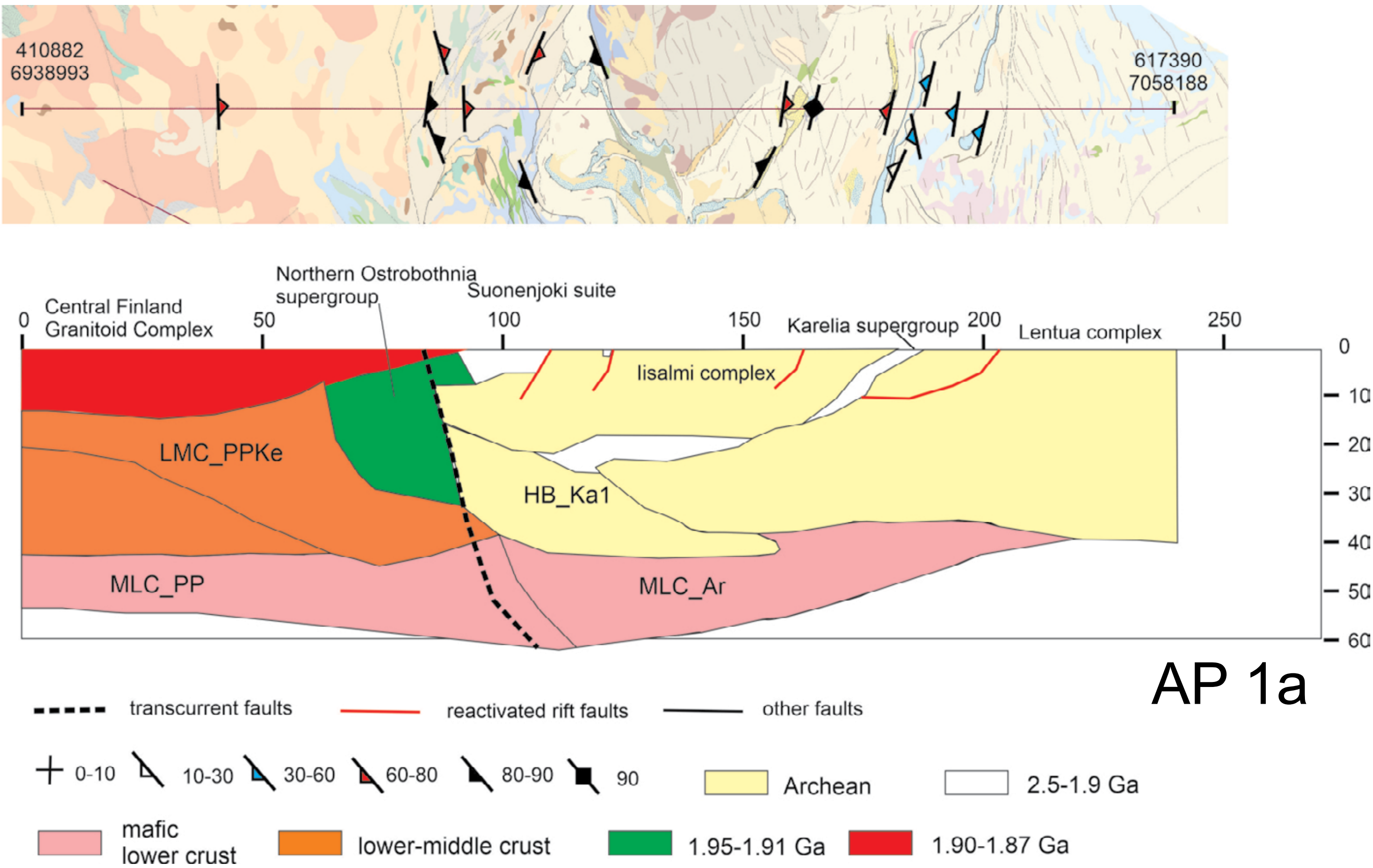
SV 4_SV 5

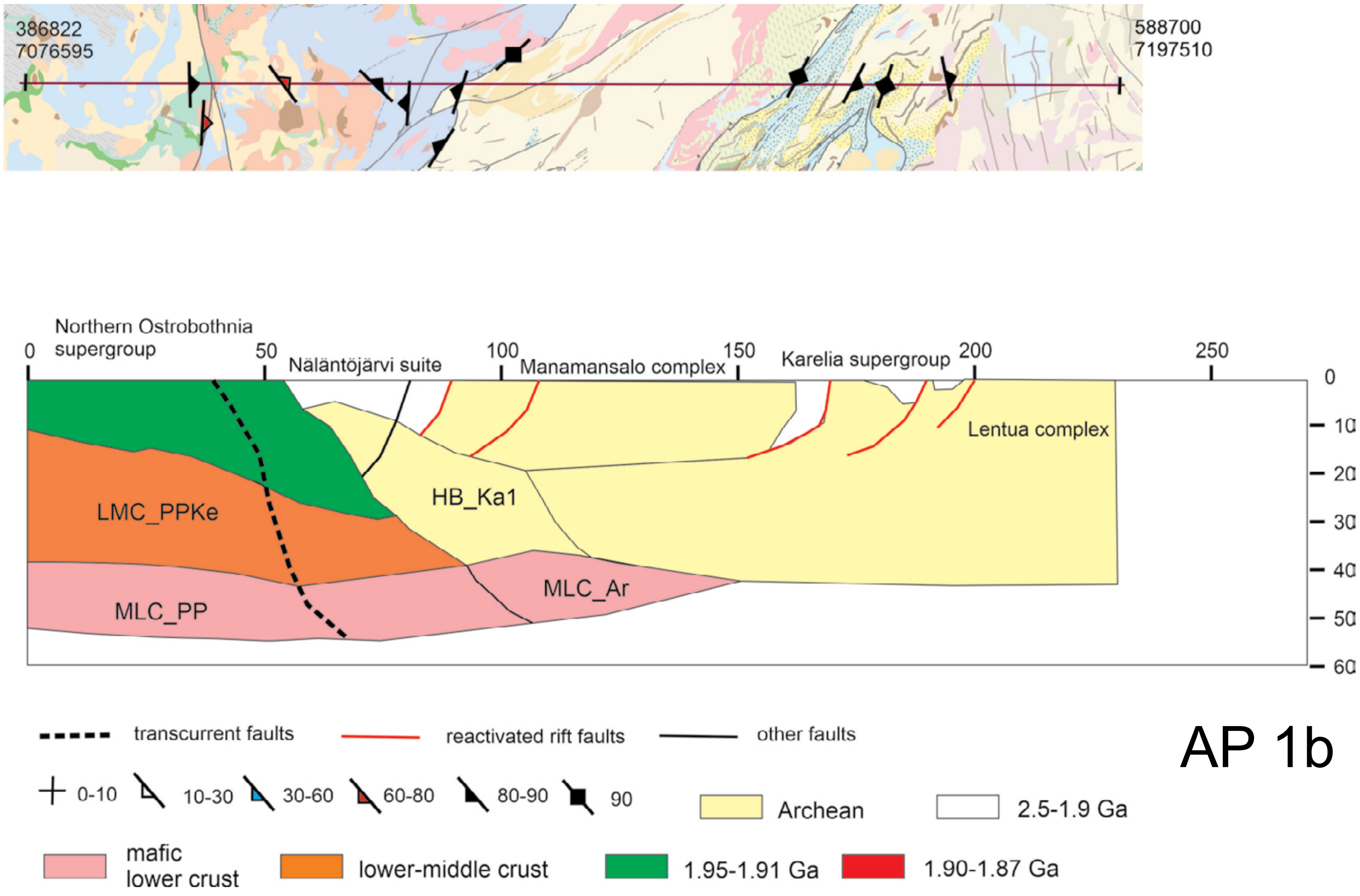
SV 6



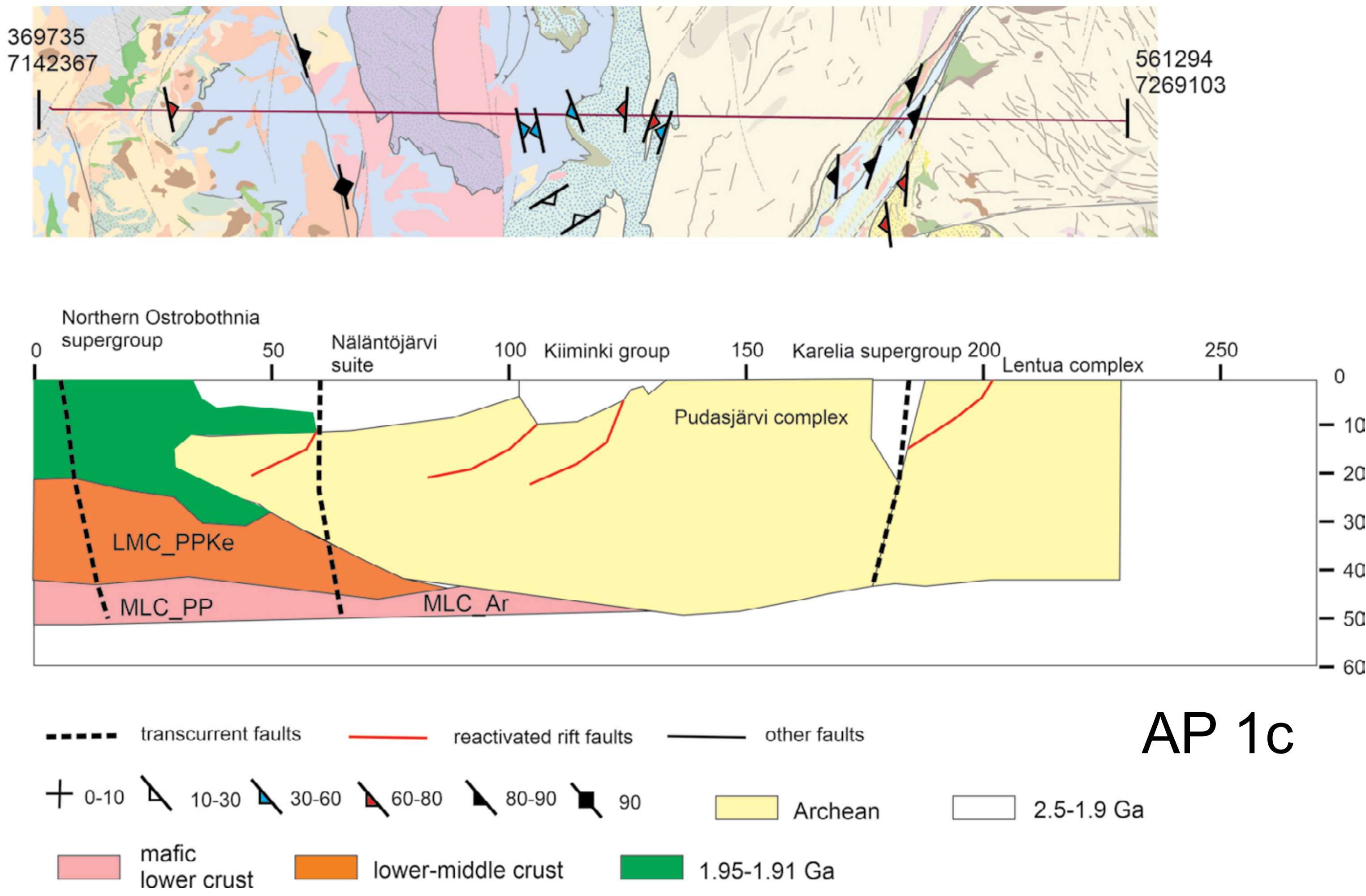

KK 1a
KK 1
KK 2
NK 4
NK 1
NK 2
NK 3a
CL 1
CL 2
NK 3
AP 4
AP 1c
AP 1b
SV 1
SV 1a
AP 1
AP 1a
AP 3
SV 6
SV 2
SV 2b
SV 1b
AP 2
SV 5
AP 3a
SV 3c
SV 4
SV 3b
SV 3
SV 2a
SV 3a


407965
7023378
641063
7160697
Central Finland
Granitoid Complex
Northern Ostrobothnia
supergroup
Nälantöjärvi
suite
Salahmi
group
Karelia supergroup
Lentua complex
0
50
100
150
200
250
0
10
20
30
40
50
60
Iisalmi complex
LMC_PPKe
HB_Ka1
MLC_PP
MLC_Ar
transcurrent faults
reactivated rift faults
other faults
0-10
10-30
30-60
60-80
80-90
90
Archean
2.5-1.9 Ga
mafic
lower crust
lower-middle crust
1.95-1.91 Ga
1.90-1.87 Ga
AP 1

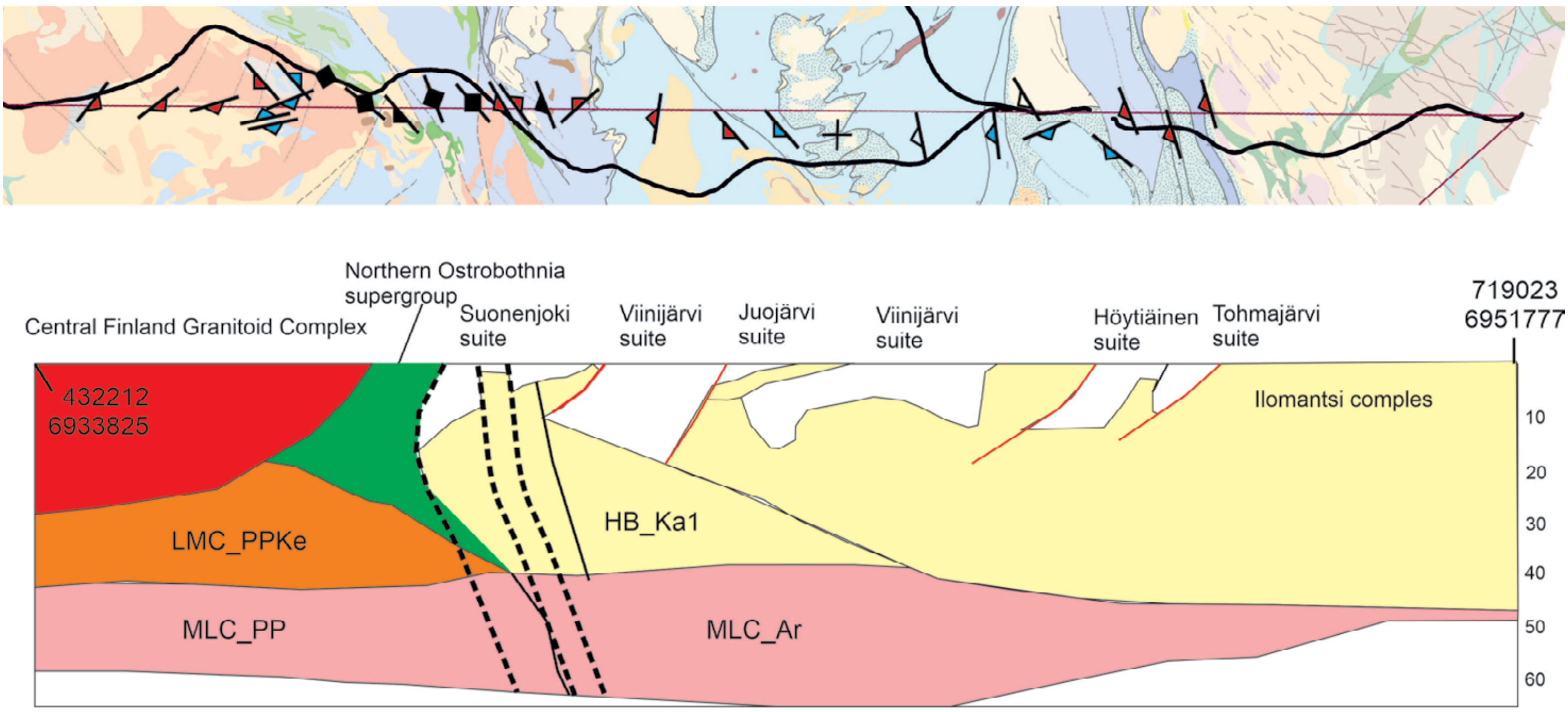

410882
6938993
617390
7058188
Central Finland
Granitoid Complex
Northern Ostrobothnia
supergroup
Suonenjoki suite
Karelia supergroup
Lentua complex
0
50
100
150
200
250
0
10
20
30
40
50
60
Iisalmi complex
LMC_PPKe
HB_Ka1
MLC_PP
MLC_Ar
transcurrent faults
reactivated rift faults
other faults
0-10
10-30
30-60
60-80
80-90
90
Archean
2.5-1.9 Ga
mafic
lower crust
lower-middle crust
1.95-1.91 Ga
1.90-1.87 Ga
AP 1a


386822
7076595
588700
7197510
Northern Ostrobothnia supergroup
Näläntöjärvi suite
Manamansalo complex
Karelia supergroup
Lentua complex
0
50
100
150
200
250
10
20
30
40
50
60
HB_Ka1
LMC_PPKe
MLC_PP
MLC_Ar
transcurrent faults
reactivated rift faults
other faults
0-10
10-30
30-60
60-80
80-90
90
Archean
2.5-1.9 Ga
mafic lower crust
lower-middle crust
1.95-1.91 Ga
1.90-1.87 Ga

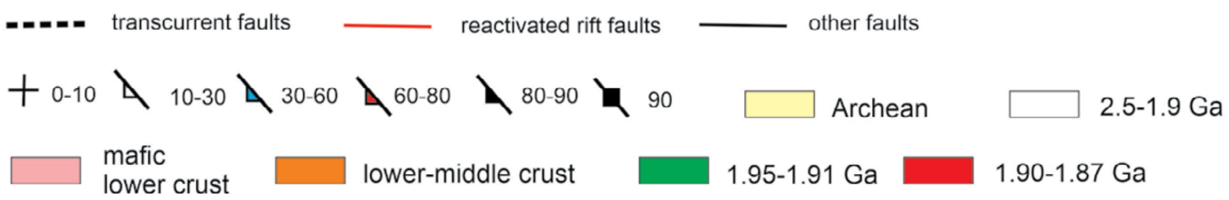
AP 1b


369735
7142367
561294
7269103
Northern Ostrobothnia supergroup
Näläntöjärvi suite
Kiiminki group
Karelia supergroup
Lentua complex
0
50
100
150
200
250
10
20
30
40
50
60
Pudasjärvi complex
LMC_PPKe
MLC_PP
MLC_Ar
transcurrent faults
reactivated rift faults
other faults
0-10
10-30
30-60
60-80
80-90
90
Archean
2.5-1.9 Ga
mafic lower crust
lower-middle crust
1.95-1.91 Ga

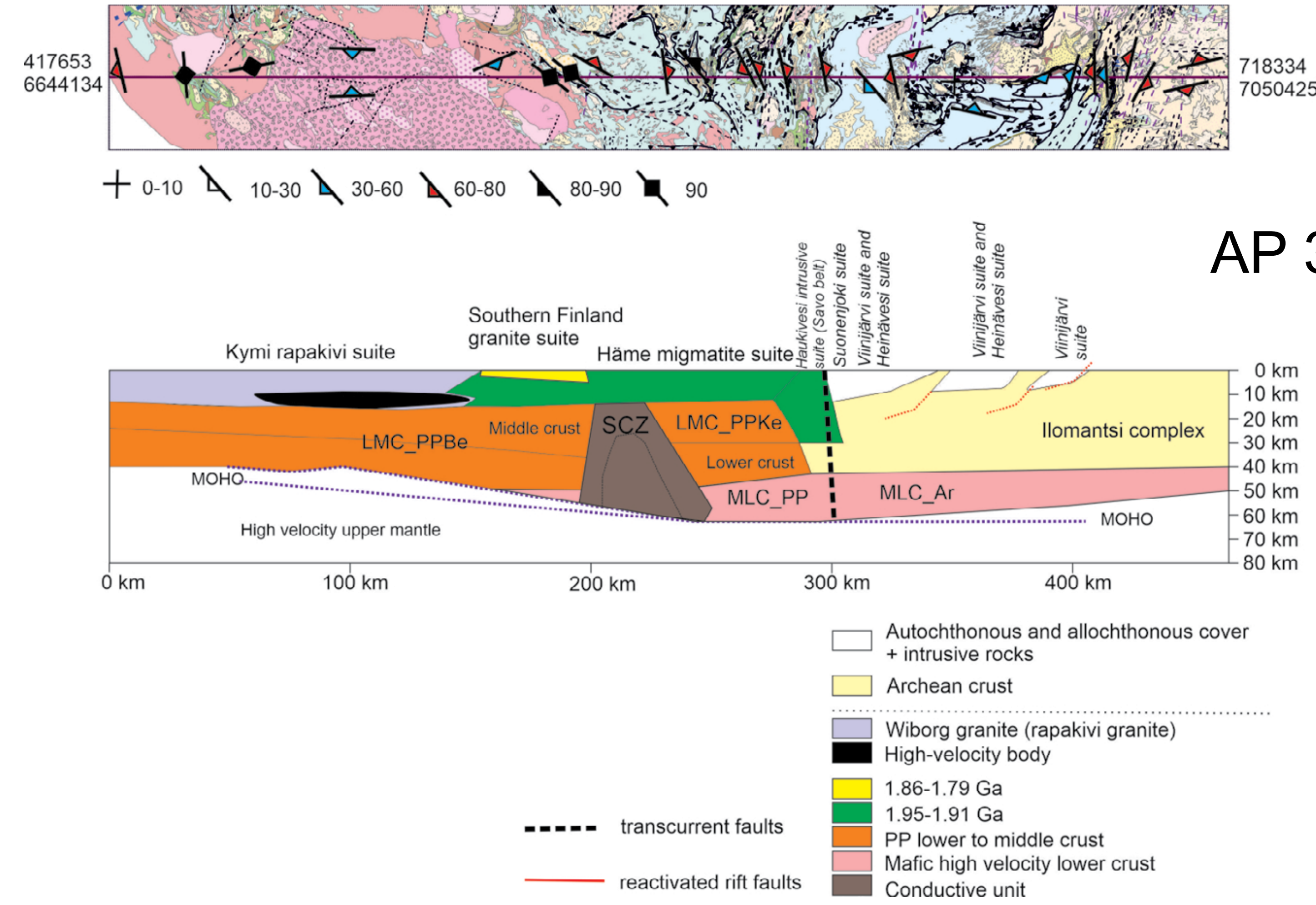
AP 1c

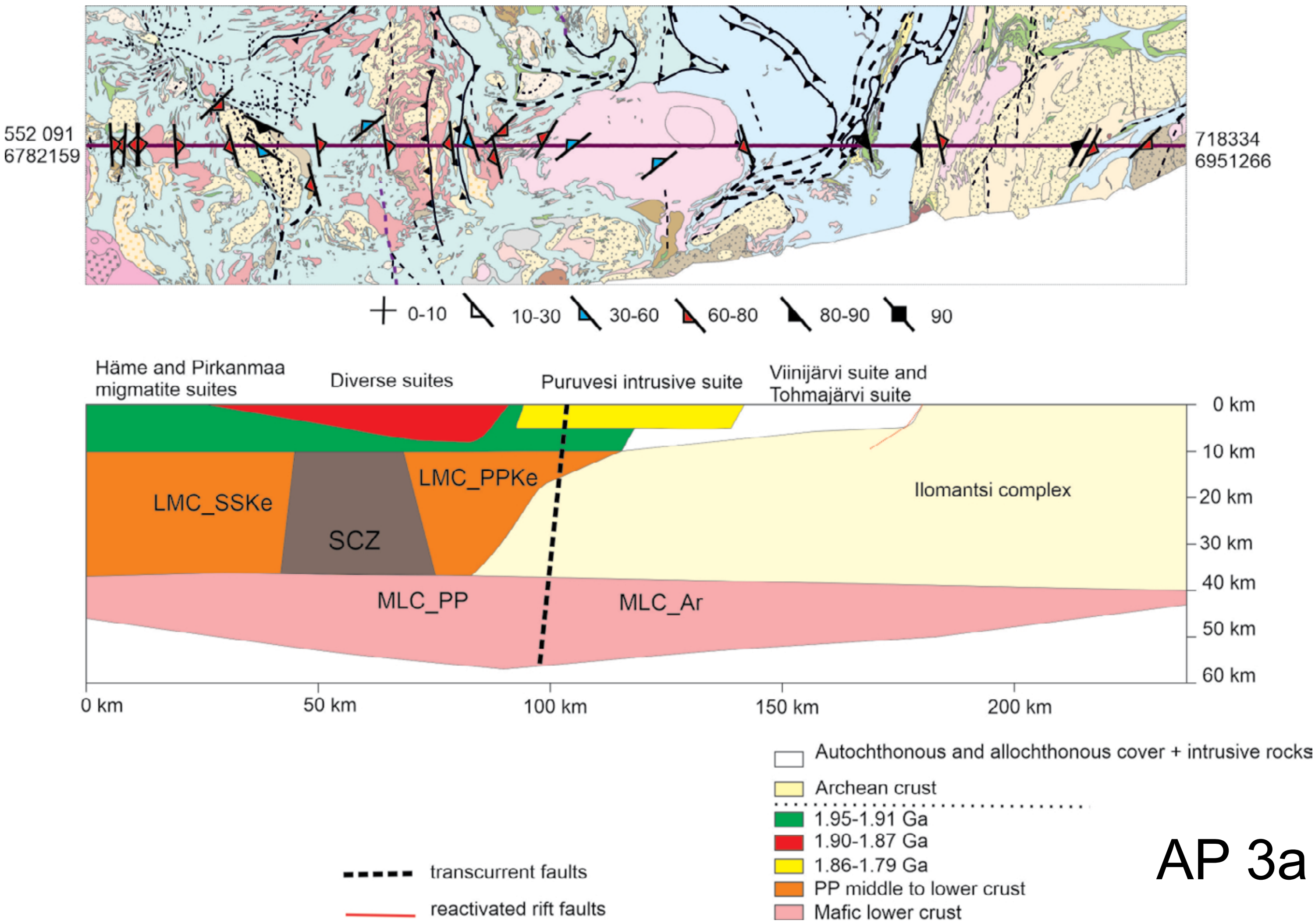

Northern Ostrobothnia supergroup
Central Finland Granitoid Complex
Suonenjoki suite
Viinijärvi suite
Juojärvi suite
Viinijärvi suite
Höytiäinen suite
Tohmajärvi suite
719023
6951777
432212
6933825
Ilomantsi comples
HB_Ka1
LMC_PPKe
MLC_PP
MLC_Ar
10
20
30
40
50
60

AP 2

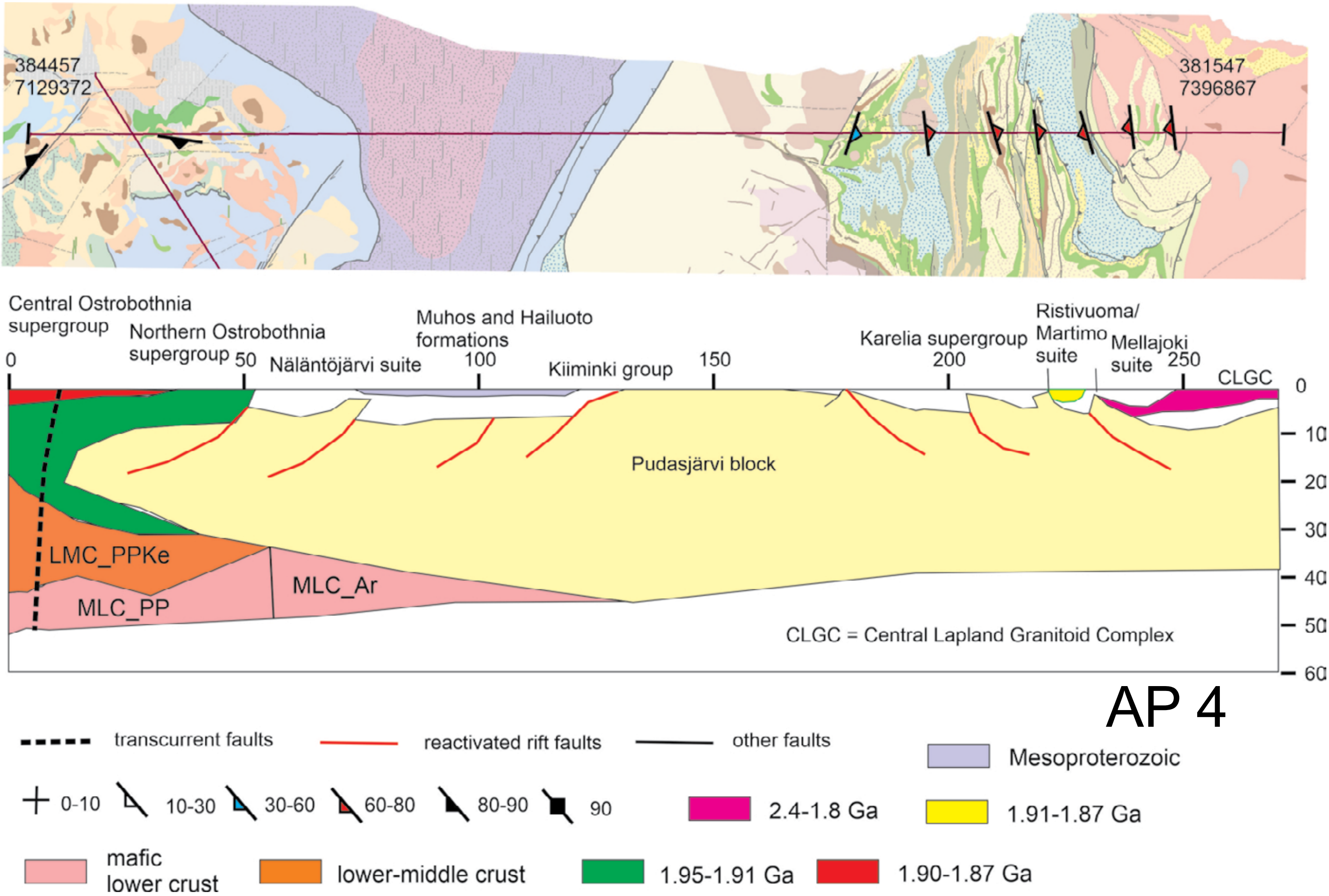

transcurrent faults
reactivated rift faults
other faults
0-10
10-30
30-60
60-80
80-90
90
Archean
2.5-1.9 Ga
mafic lower crust
lower-middle crust
1.95-1.91 Ga
1.90-1.87 Ga

AP 3

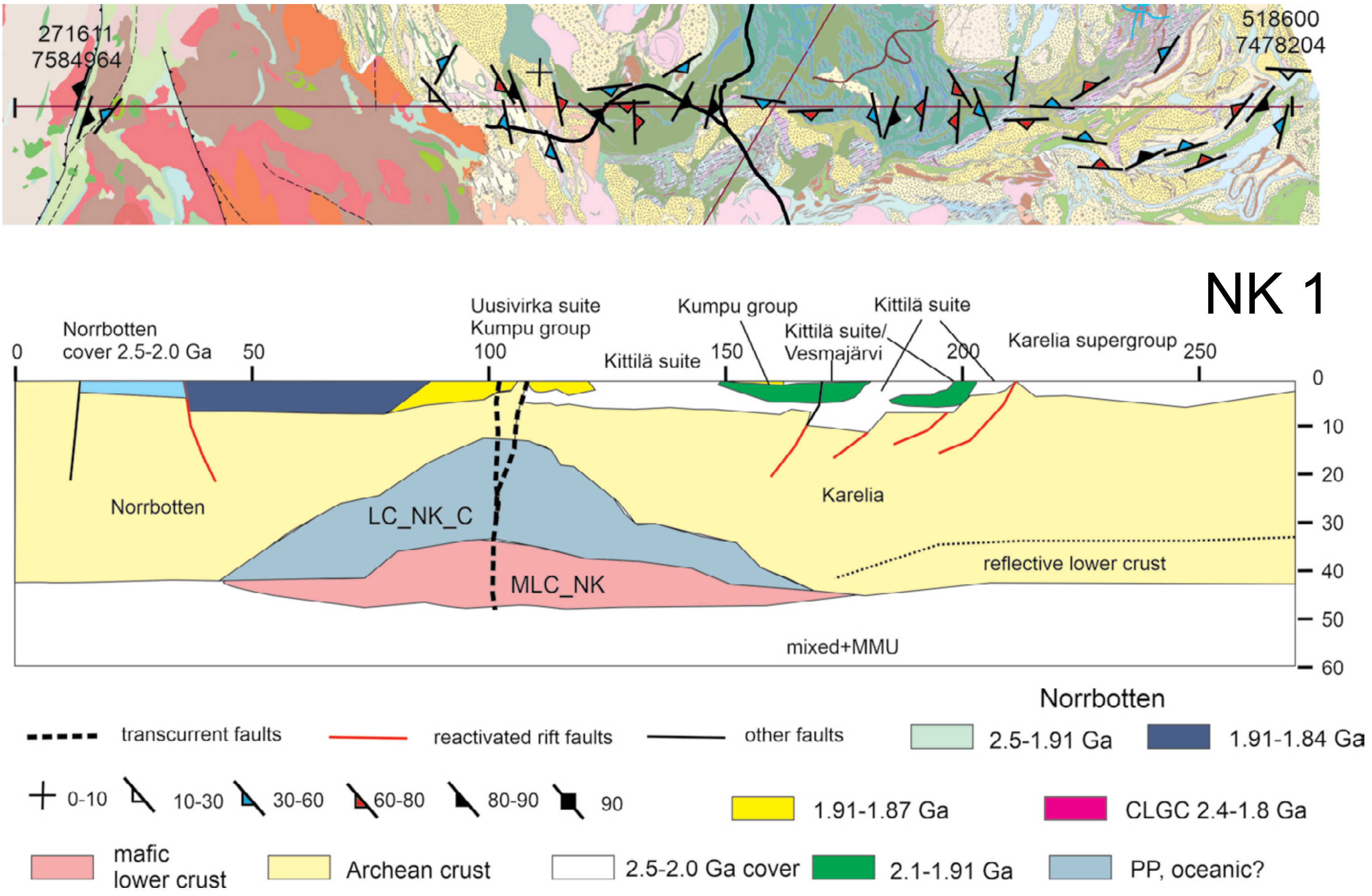

417653
6644134
718334
7050425
0-10
10-30
30-60
60-80
80-90
90
Kymi rapakivi suite
Southern Finland
granite suite
Häme migmatite suite
Haukivesi intrusive suite (Savo belt)
Suonenjoki suite
Viinijärvi suite and Heinävesi suite
Viinijärvi suite and Heinävesi suite
Viinijärvi suite
LMC_PPBe
Middle crust
SCZ
LMC_PPKe
Lower crust
MLC_PP
MLC_Ar
Ilomantsi complex
MOHO
MOHO
High velocity upper mantle
0 km
10 km
20 km
30 km
40 km
50 km
60 km
70 km
80 km
0 km
100 km
200 km
300 km
400 km
Autochthonous and allochthonous cover
+ intrusive rocks
Archean crust
Wiborg granite (rapakivi granite)
High-velocity body
1.86-1.79 Ga
1.95-1.91 Ga
PP lower to middle crust
Mafic high velocity lower crust
Conductive unit
transcurrent faults
reactivated rift faults

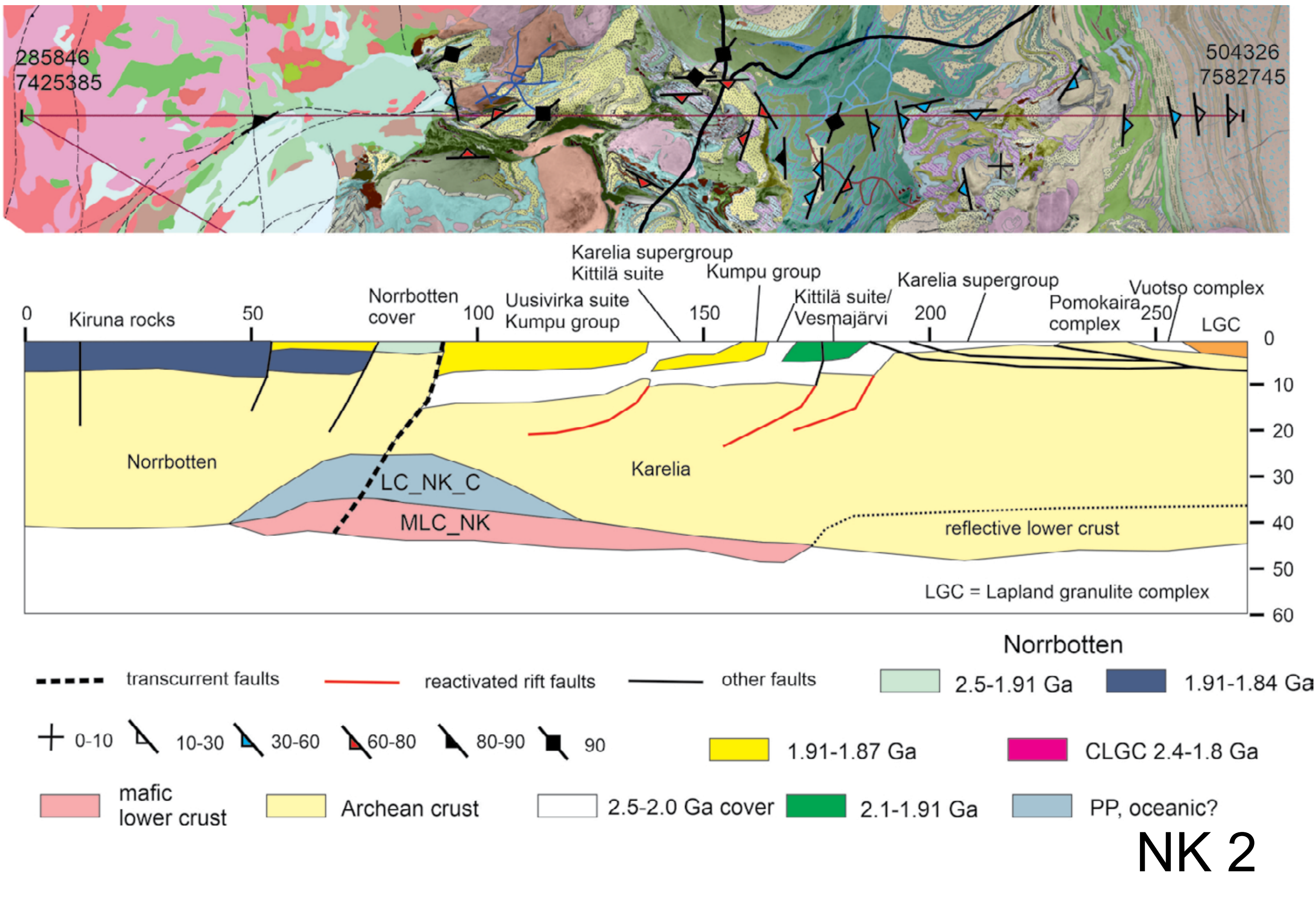

552 091
6782159
718334
6951266
0-10
10-30
30-60
60-80
80-90
90
Häme and Pirkanmaa
migmatite suites
Diverse suites
Puruvesi intrusive suite
Viinijärvi suite and
Tohmajärvi suite
LMC_SSKe
SCZ
LMC_PPKe
Ilomantsi complex
MLC_PP
MLC_Ar
0 km
10 km
20 km
30 km
40 km
50 km
60 km
0 km
50 km
100 km
150 km
200 km
Autochthonous and allochthonous cover + intrusive rocks
Archean crust
1.95-1.91 Ga
1.90-1.87 Ga
1.86-1.79 Ga
PP middle to lower crust
Mafic lower crust
transcurrent faults
reactivated rift faults

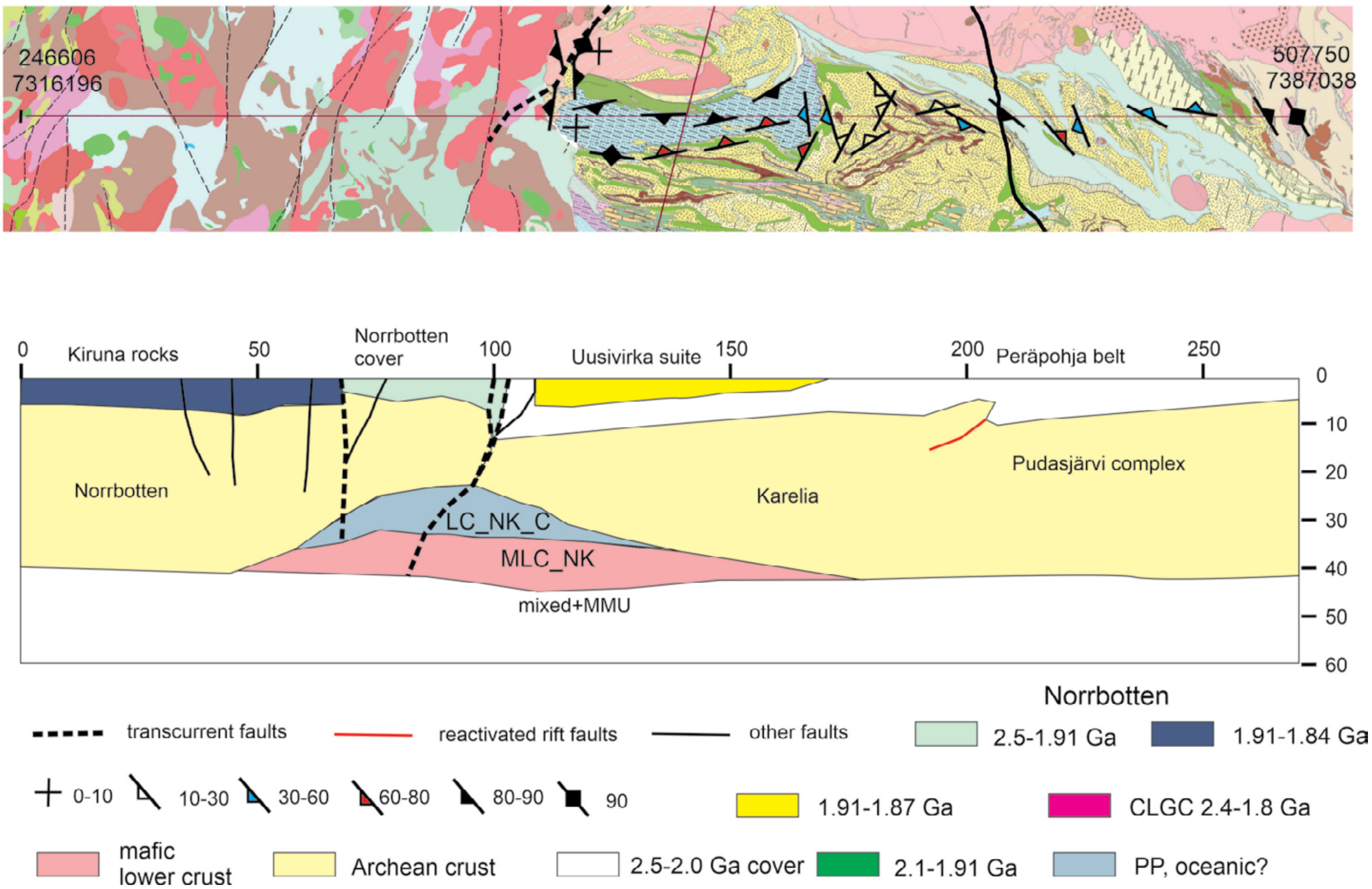
AP 3a


384457
7129372
381547
7396867
Central Ostrobothnia supergroup
Northern Ostrobothnia supergroup
Näläntöjärvi suite
Muhos and Hailuoto formations
Kiiminki group
Karelia supergroup
Ristivuoma/ Martimo suite
Mellajoki suite
CLGC
0
50
100
150
200
250
0
10
20
30
40
50
60
Pudasjärvi block
LMC_PPKe
MLC_PP
MLC_Ar
CLGC = Central Lapland Granitoid Complex
transcurrent faults
reactivated rift faults
other faults
Mesoproterozoic
0-10
10-30
30-60
60-80
80-90
90
2.4-1.8 Ga
1.91-1.87 Ga
mafic lower crust
lower-middle crust
1.95-1.91 Ga
1.90-1.87 Ga

AP 4

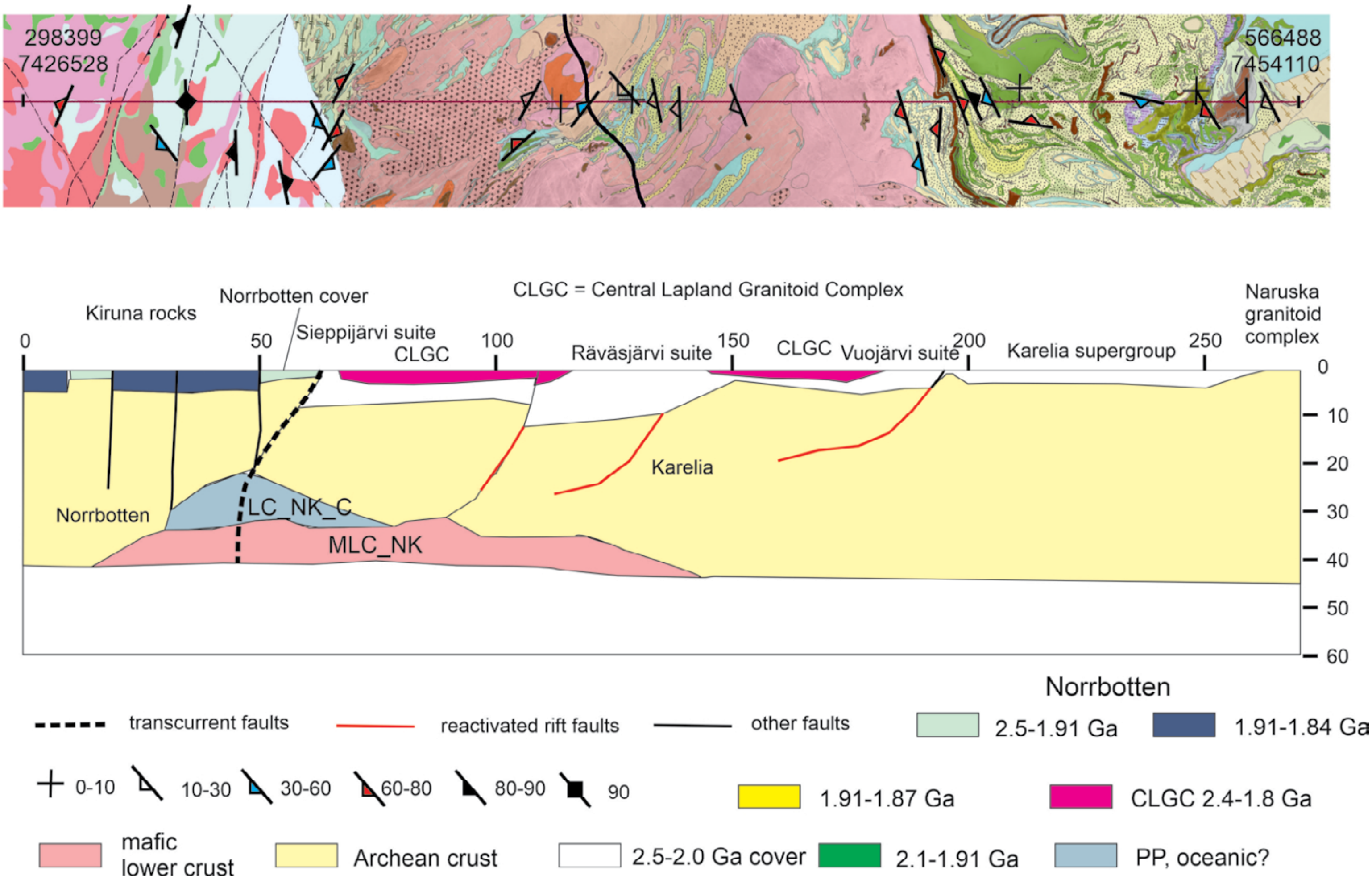

271611
7584964
518600
7478204
NK 1
Norrbotten
cover 2.5-2.0 Ga
Uusivirka suite
Kumpu group
Kittilä suite
Kumpu group
Kittilä suite/
Vesmajärvi
Kittilä suite
Karelia supergroup
0
50
100
150
200
250
0
10
20
30
40
50
60
Norrbotten
LC_NK_C
MLC_NK
Karelia
reflective lower crust
mixed+MMU
transcurrent faults
reactivated rift faults
other faults
Norrbotten
2.5-1.91 Ga
1.91-1.84 Ga
0-10
10-30
30-60
60-80
80-90
90
1.91-1.87 Ga
CLGC 2.4-1.8 Ga
mafic
lower crust
Archean crust
2.5-2.0 Ga cover
2.1-1.91 Ga
PP, oceanic?


285846
7425385
504326
7582745
Kiruna rocks
Norrbotten
cover
Uusivirka suite
Kumpu group
Karelia supergroup
Kittilä suite
Kumpu group
Kittilä suite/
Vesmajärvi
Karelia supergroup
Pomokaira
complex
Vuotso complex
LGC
0
50
100
150
200
250
0
10
20
30
40
50
60
Norrbotten
LC_NK_C
MLC_NK
Karelia
reflective lower crust
LGC = Lapland granulite complex
transcurrent faults
reactivated rift faults
other faults
Norrbotten
2.5-1.91 Ga
1.91-1.84 Ga
0-10
10-30
30-60
60-80
80-90
90
1.91-1.87 Ga
CLGC 2.4-1.8 Ga
mafic
lower crust
Archean crust
2.5-2.0 Ga cover
2.1-1.91 Ga
PP, oceanic?
NK 2



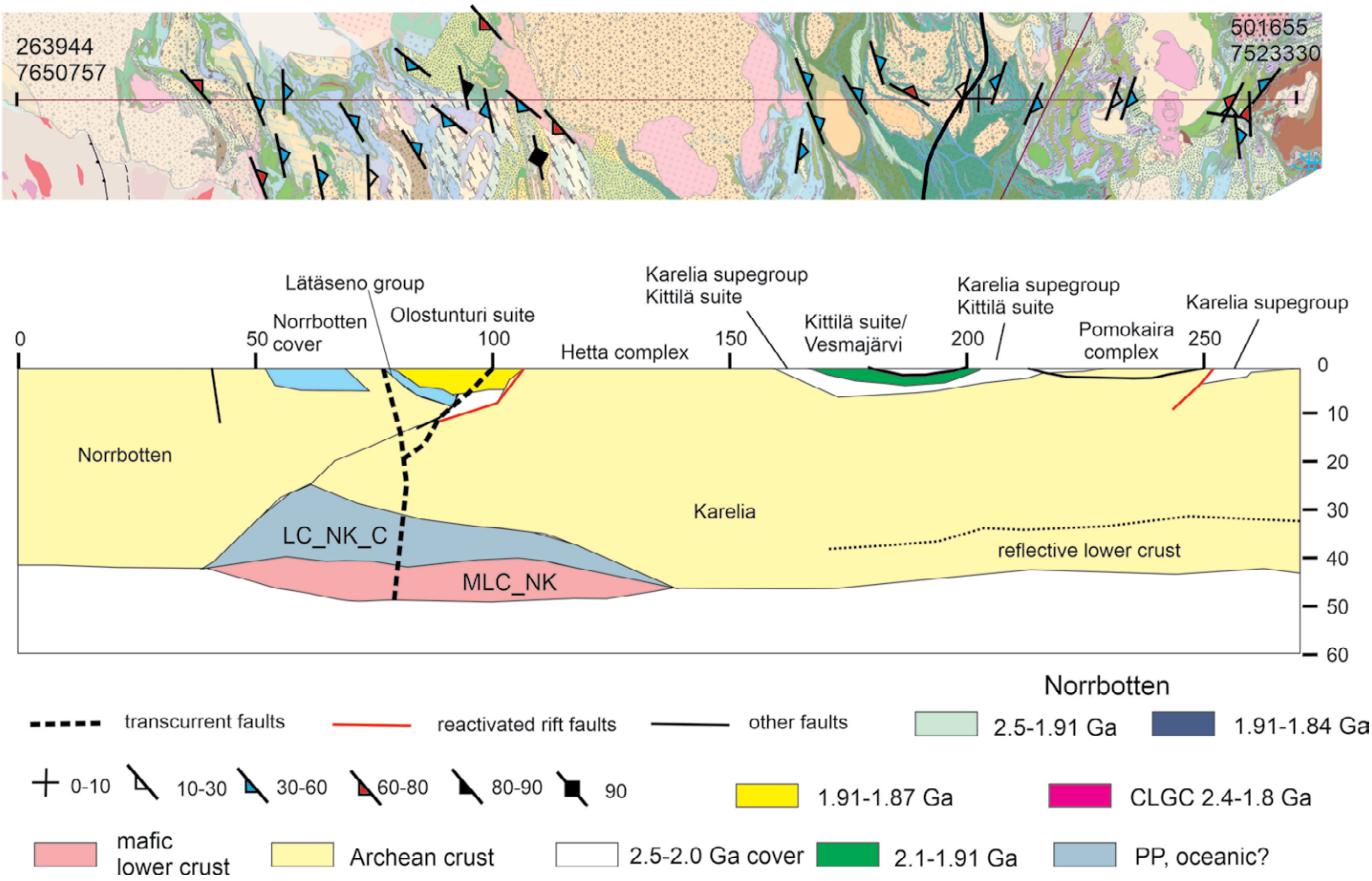
246606
7316196
507750
7387038
0
Kiruna rocks
50
Norrbotten
cover
100
Uusivirka suite
150
200
Peräpohja belt
250
0
10
20
30
40
50
60
Norrbotten
LC_NK_C
MLC_NK
mixed+MMU
Karelia
Pudasjärvi complex
Norrbotten
transcurrent faults
reactivated rift faults
other faults
2.5-1.91 Ga
1.91-1.84 Ga
0-10
10-30
30-60
60-80
80-90
90
1.91-1.87 Ga
CLGC 2.4-1.8 Ga
mafic
lower crust
Archean crust
2.5-2.0 Ga cover
2.1-1.91 Ga
PP, oceanic?

NK 3

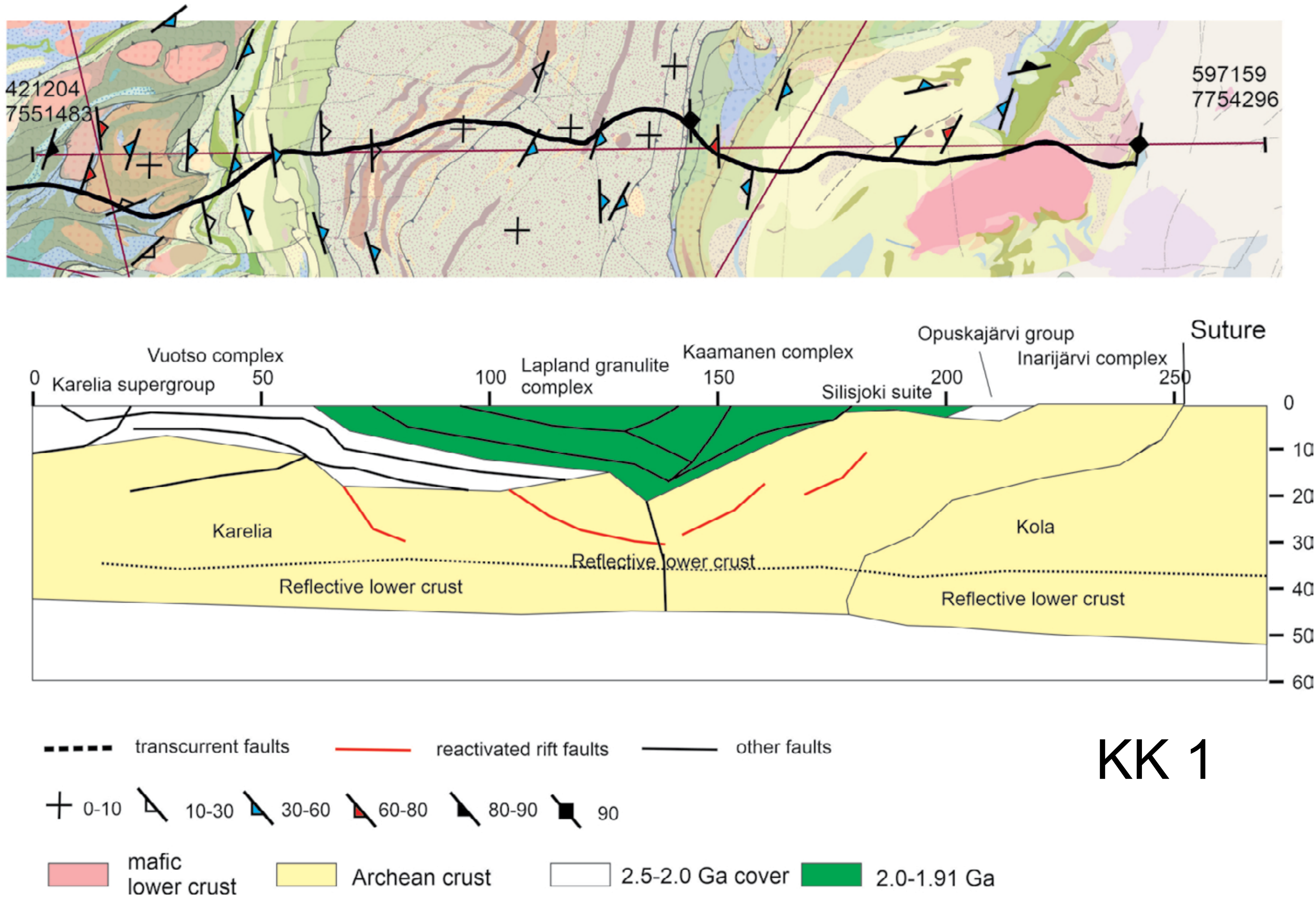


298399
7426528
566488
7454110
CLGC = Central Lapland Granitoid Complex
Kiruna rocks
Norrbotten cover
Sieppijärvi suite
CLGC
Rävåsjärvi suite
CLGC
Vuojärvi suite
Karelia supergroup
Naruska
granitoid
complex
0
50
100
150
200
250
0
10
20
30
40
50
60
Norrbotten
LC_NK_C
MLC_NK
Karelia
Norrbotten
transcurrent faults
reactivated rift faults
other faults
2.5-1.91 Ga
1.91-1.84 Ga
0-10
10-30
30-60
60-80
80-90
90
1.91-1.87 Ga
CLGC 2.4-1.8 Ga
mafic
lower crust
Archean crust
2.5-2.0 Ga cover
2.1-1.91 Ga
PP, oceanic?

NK 3a

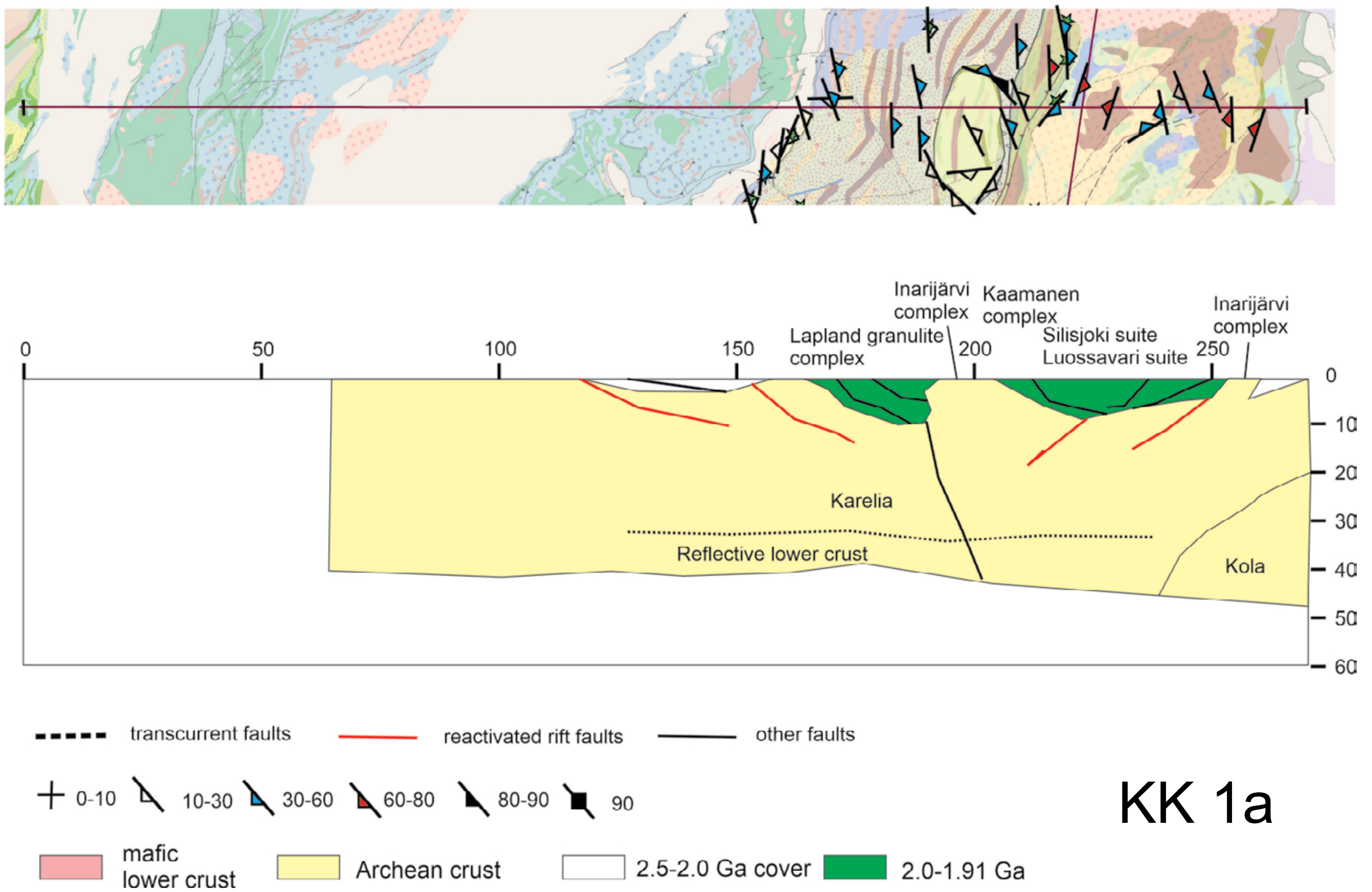

263944
7650757
501655
7523330
Lätäseno group
Norrbotten cover
Olostunturi suite
Karelia supegroup
Kittilä suite
Hetta complex
Kittilä suite/
Vesmajärvi
Karelia supegroup
Kittilä suite
Pomokaira complex
Karelia supegroup
0
50
100
150
200
250
0
10
20
30
40
50
60
Norrbotten
Karelia
LC_NK_C
MLC_NK
reflective lower crust
Norrbotten
transcurrent faults
reactivated rift faults
other faults
2.5-1.91 Ga
1.91-1.84 Ga
0-10
10-30
30-60
60-80
80-90
90
1.91-1.87 Ga
CLGC 2.4-1.8 Ga
mafic lower crust
Archean crust
2.5-2.0 Ga cover
2.1-1.91 Ga
PP, oceanic?

NK 4



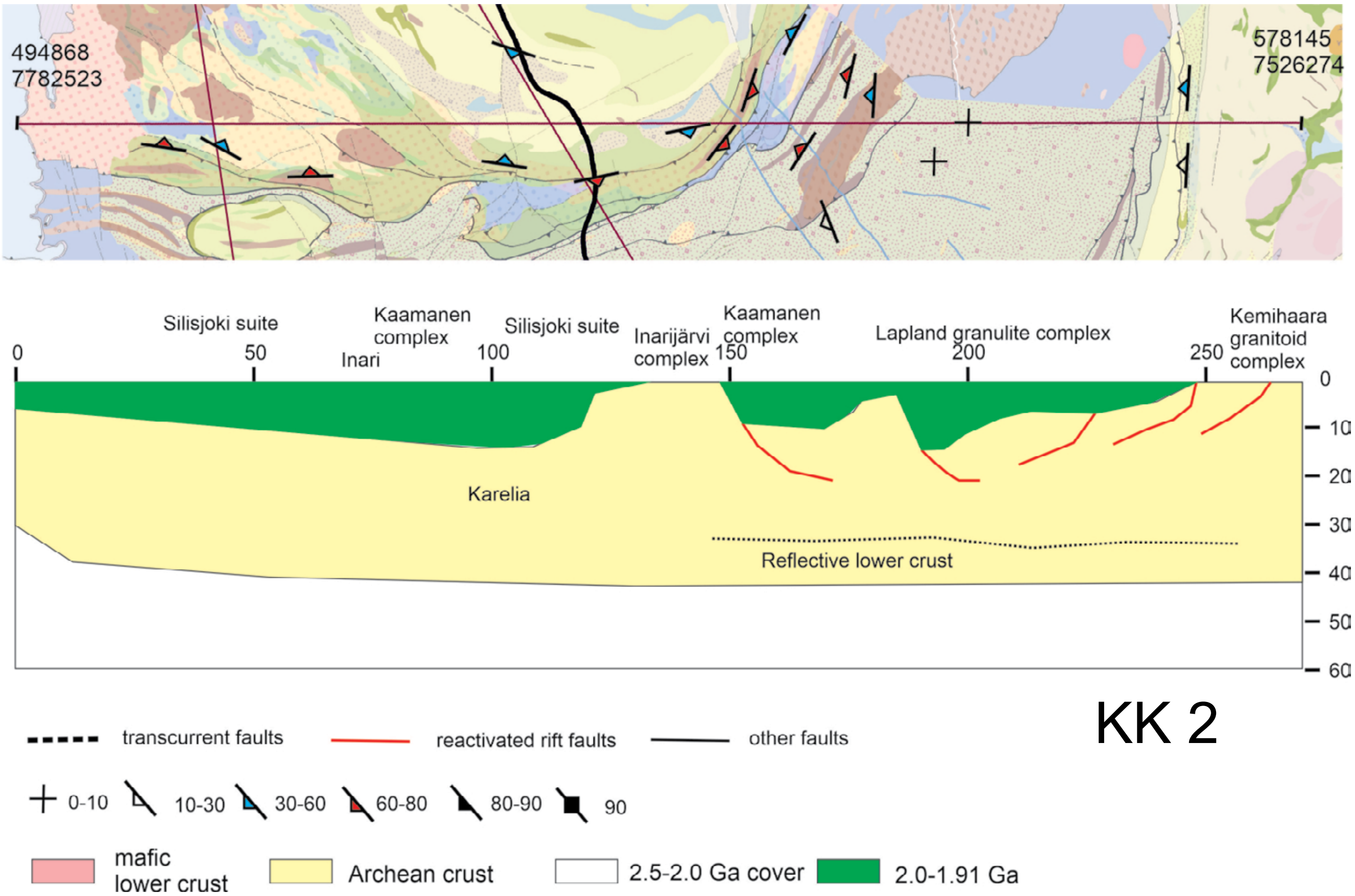
421204
7551483
597159
7754296
Vuotso complex
Karelia supergroup
Lapland granulite complex
Kaamanen complex
Opuskajärvi group
Inarijärvi complex
Silisjoki suite
Suture
0
50
100
150
200
250
10
20
30
40
50
60
Karelia
Kola
Reflective lower crust
Reflective lower crust
Reflective lower crust
transcurrent faults
reactivated rift faults
other faults
0-10
10-30
30-60
60-80
80-90
90
mafic lower crust
Archean crust
2.5-2.0 Ga cover
2.0-1.91 Ga

KK 1



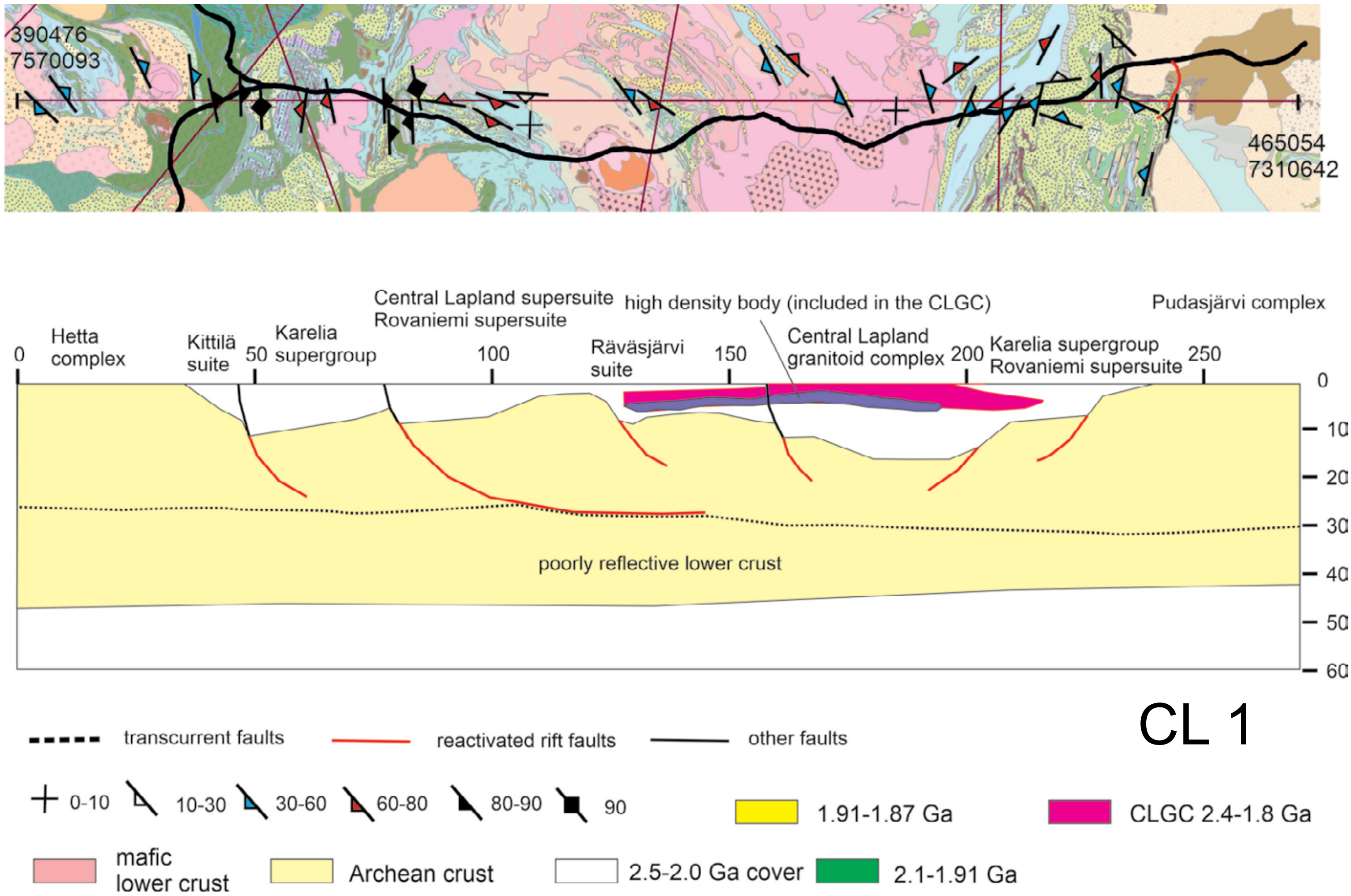
Inarijärvi complex
Kaamanen complex
Lapland granulite complex
Silisjoki suite
Luossavari suite
Inarijärvi complex
0
50
100
150
200
250
10
20
30
40
50
60
Karelia
Reflective lower crust
Kola
transcurrent faults
reactivated rift faults
other faults
0-10
10-30
30-60
60-80
80-90
90
mafic lower crust
Archean crust
2.5-2.0 Ga cover
2.0-1.91 Ga

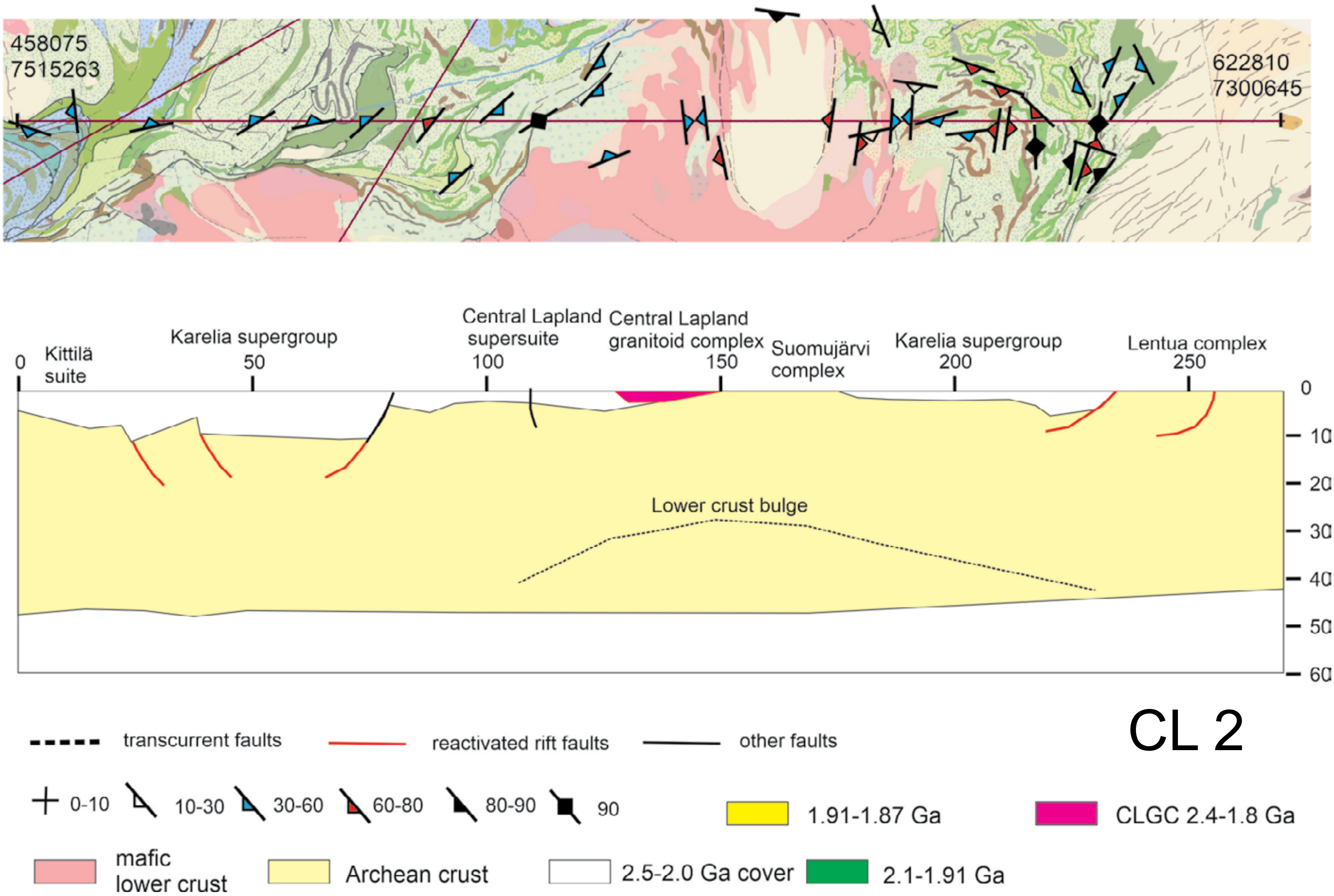
KK 1a

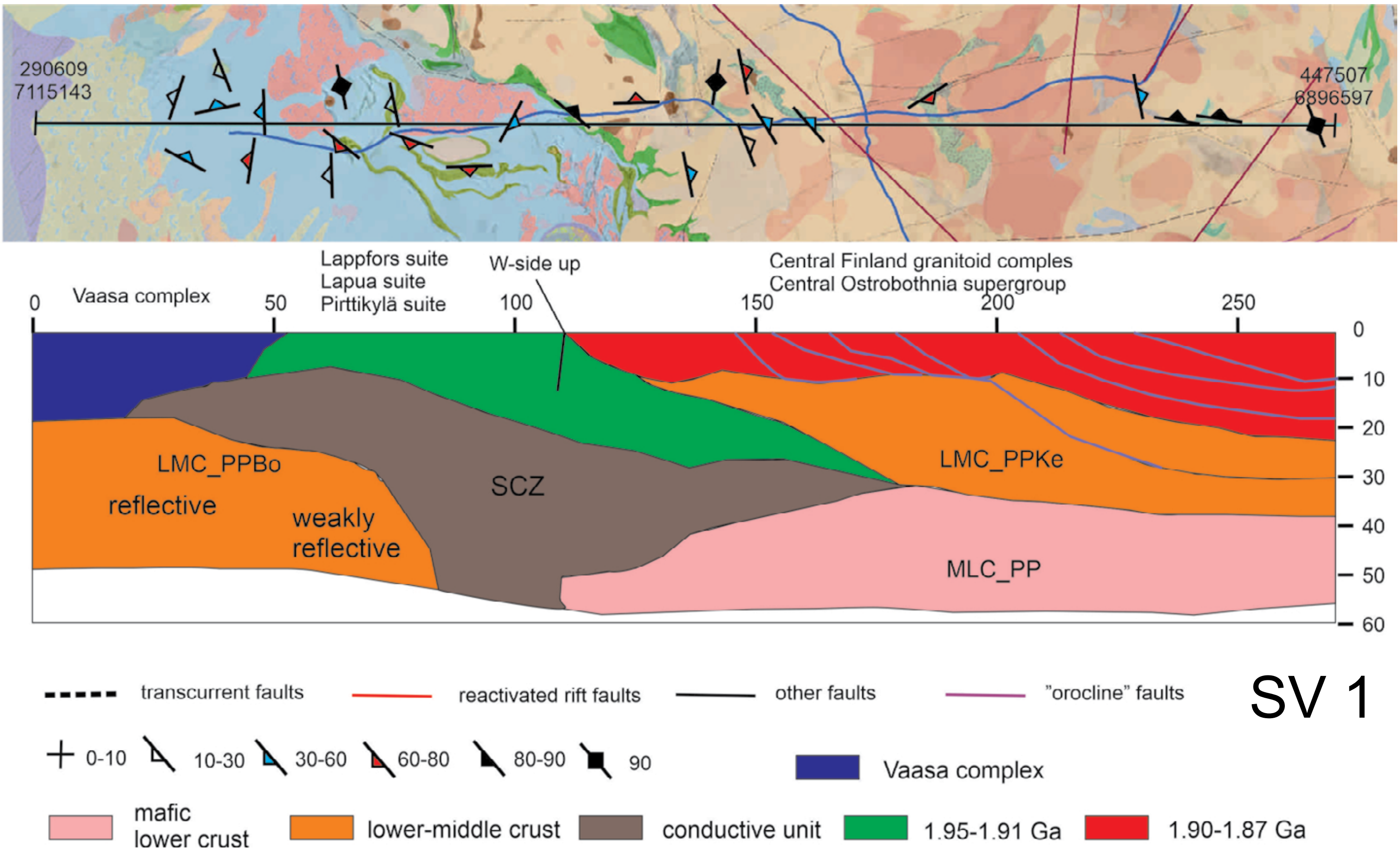


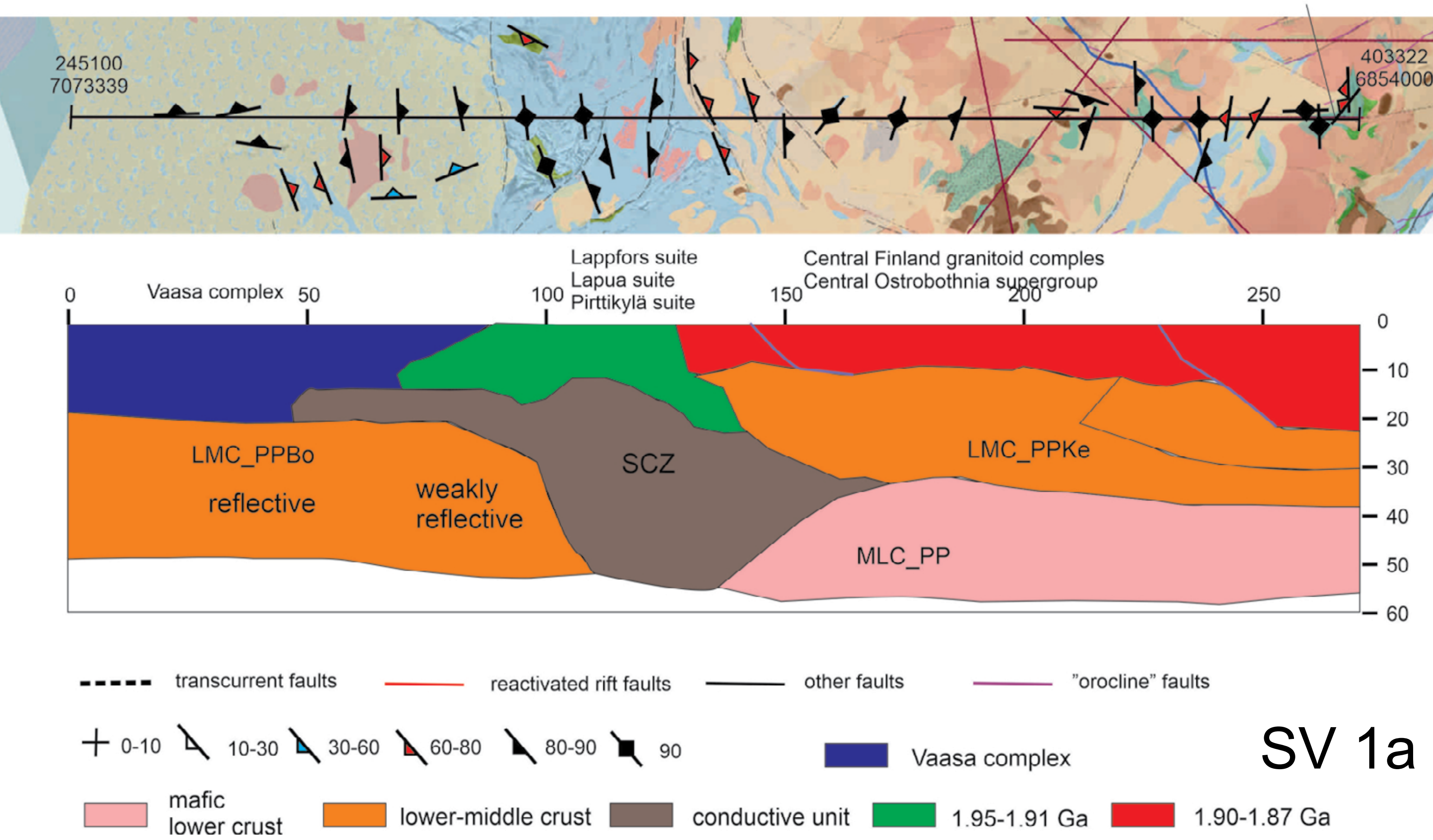
494868
7782523
578145
7526274
Silisjoki suite
Kaamanen complex
Inari
Silisjoki suite
Inarijärvi complex
Kaamanen complex
Lapland granulite complex
Kemihaara granitoid complex
0
50
100
150
200
250
0
10
20
30
40
50
60
Karelia
Reflective lower crust
transcurrent faults
reactivated rift faults
other faults
0-10
10-30
30-60
60-80
80-90
90
mafic lower crust
Archean crust
2.5-2.0 Ga cover
2.0-1.91 Ga

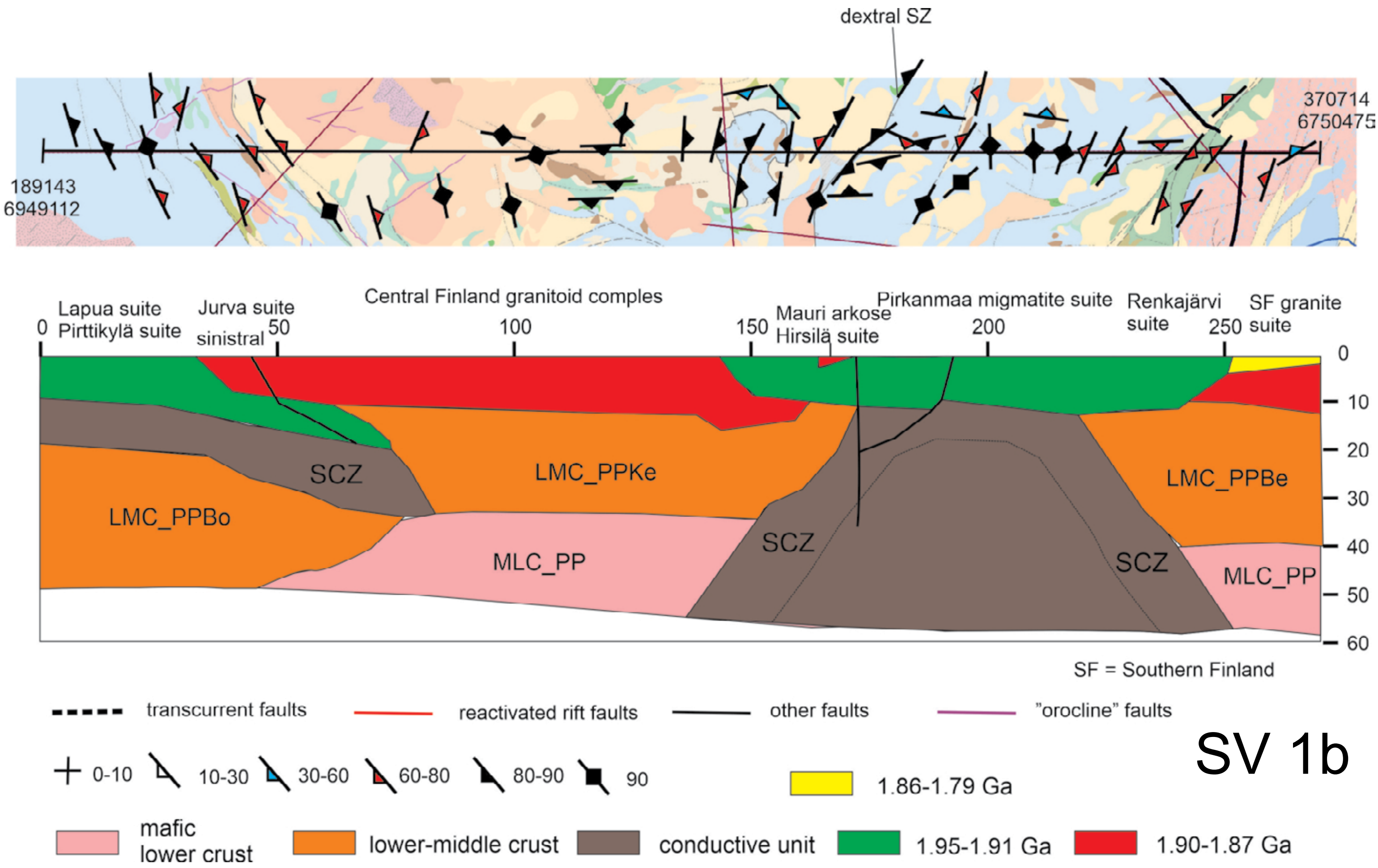
KK 2


390476
7570093
465054
7310642
Hetta complex
Kittilä suite
Karelia supergroup
Central Lapland supersuite
Rovaniemi supersuite
high density body (included in the CLGC)
Rävasjärvi suite
Central Lapland granitoid complex
Karelia supergroup
Rovaniemi supersuite
Pudasjärvi complex
0
50
100
150
200
250
poorly reflective lower crust
transcurrent faults
reactivated rift faults
other faults
CL 1
0-10
10-30
30-60
60-80
80-90
90
1.91-1.87 Ga
CLGC 2.4-1.8 Ga
mafic lower crust
Archean crust
2.5-2.0 Ga cover
2.1-1.91 Ga

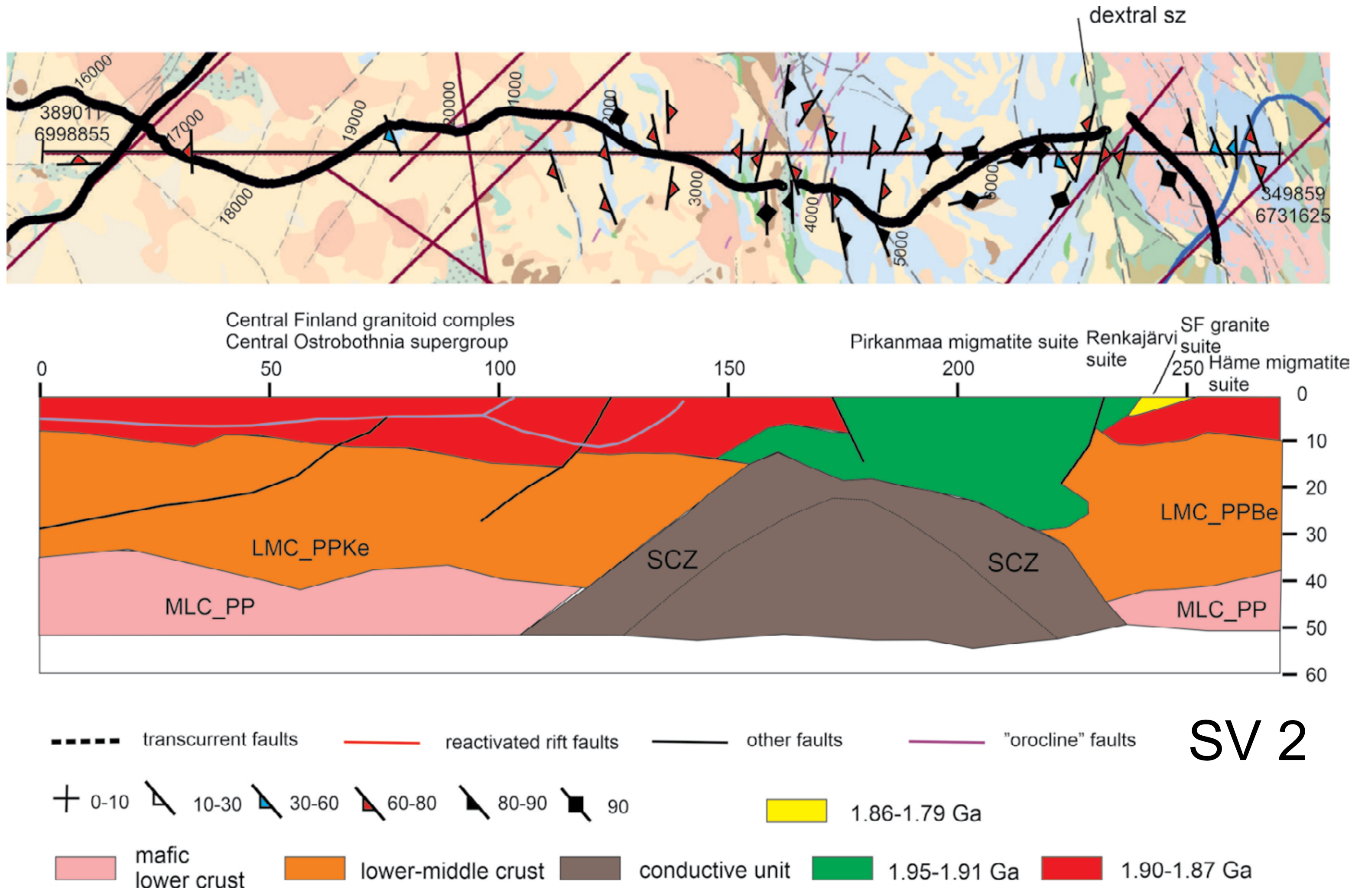

458075
7515263
622810
7300645
Kittilä suite
Karelia supergroup
Central Lapland supersuite
Central Lapland granitoid complex
Suomujärvi complex
Karelia supergroup
Lentua complex
0
50
100
150
200
250
Lower crust bulge
transcurrent faults
reactivated rift faults
other faults
CL 2
0-10
10-30
30-60
60-80
80-90
90
1.91-1.87 Ga
CLGC 2.4-1.8 Ga
mafic lower crust
Archean crust
2.5-2.0 Ga cover
2.1-1.91 Ga


290609
7115143
447507
6896597
0
Vaasa complex
50
Lappfors suite
Lapua suite
Pirttikylä suite
W-side up
100
Central Finland granitoid comples
Central Ostrobothnia supergroup
150
200
250
0
10
20
30
40
50
60
LMC_PPBo
reflective
weakly
reflective
SCZ
LMC_PPKe
MLC_PP
transcurrent faults
reactivated rift faults
other faults
"orocline" faults
0-10
10-30
30-60
60-80
80-90
90
Vaasa complex
mafic
lower crust
lower-middle crust
conductive unit
1.95-1.91 Ga
1.90-1.87 Ga
SV 1

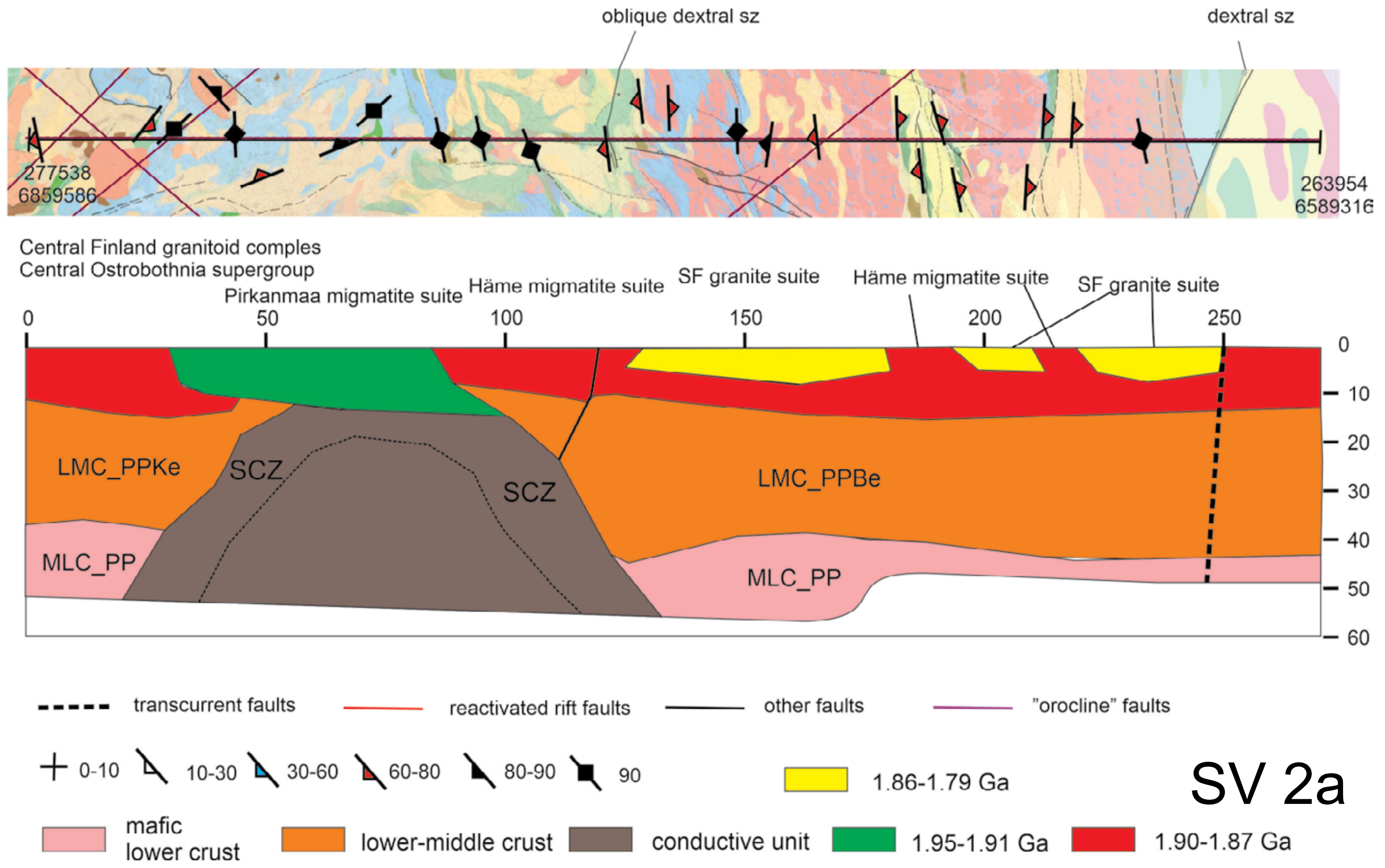

245100
7073339
403322
6854000
0
Vaasa complex
50
100
Lappfors suite
Lapua suite
Pirttikylä suite
150
Central Finland granitoid comples
Central Ostrobothnia supergroup
200
250
0
10
20
30
40
50
60
LMC_PPBo
reflective
weakly
reflective
SCZ
LMC_PPKe
MLC_PP
transcurrent faults
reactivated rift faults
other faults
"orocline" faults
0-10
10-30
30-60
60-80
80-90
90
Vaasa complex
mafic
lower crust
lower-middle crust
conductive unit
1.95-1.91 Ga
1.90-1.87 Ga
SV 1a


dextral SZ
189143
6949112
370714
6750475
Lapua suite
Pirttikylä suite
Jurva suite
sinistral
Central Finland granitoid comples
Mauri arkose
Hirsilä suite
Pirkanmaa migmatite suite
Renkajärvi suite
SF granite suite
0
50
100
150
200
250
0
10
20
30
40
50
60
SCZ
LMC_PPBo
LMC_PPKe
MLC_PP
SCZ
SCZ
LMC_PPBe
MLC_PP
SF = Southern Finland
transcurrent faults
reactivated rift faults
other faults
"orocline" faults
0-10
10-30
30-60
60-80
80-90
90
1.86-1.79 Ga
mafic lower crust
lower-middle crust
conductive unit
1.95-1.91 Ga
1.90-1.87 Ga

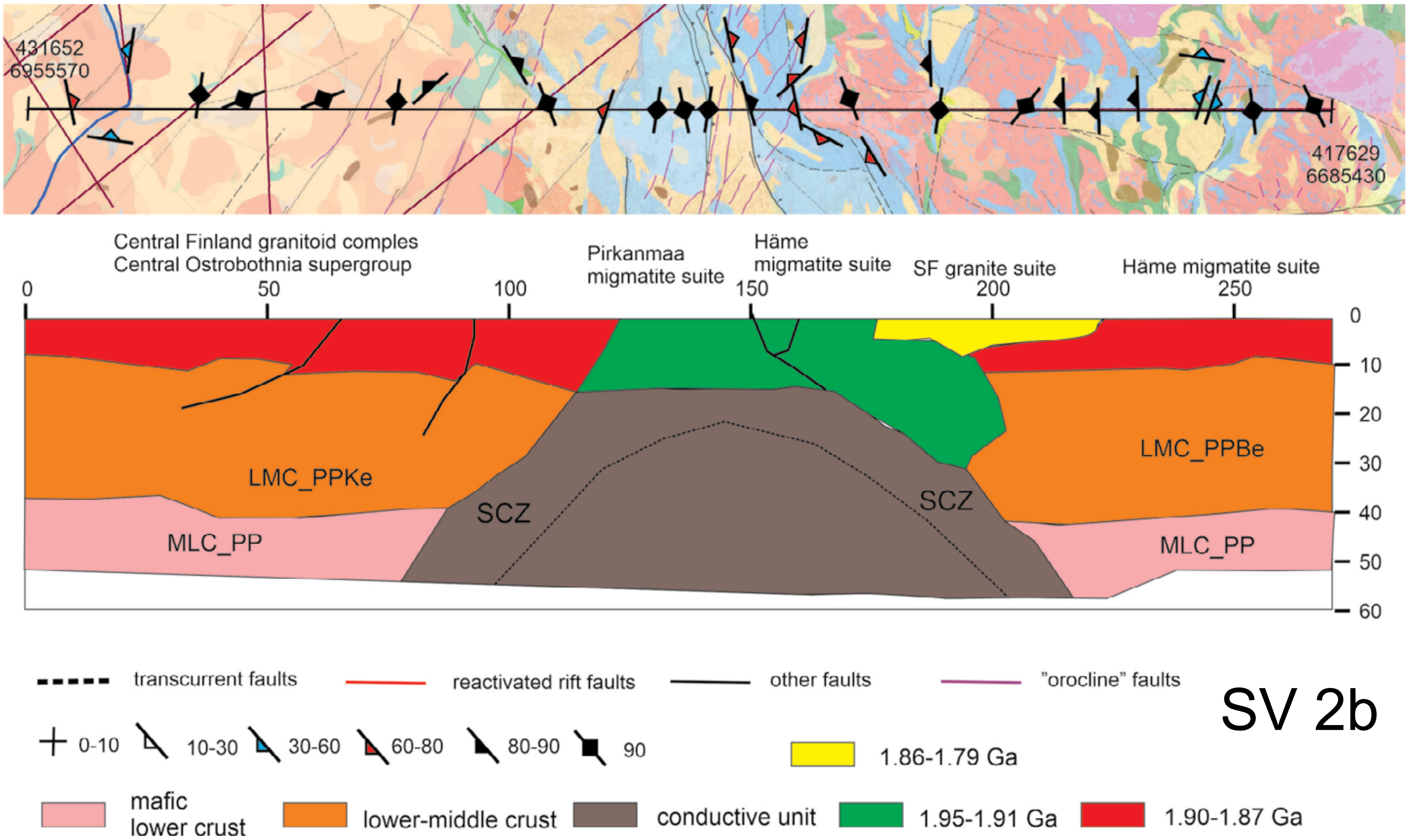
SV 1b

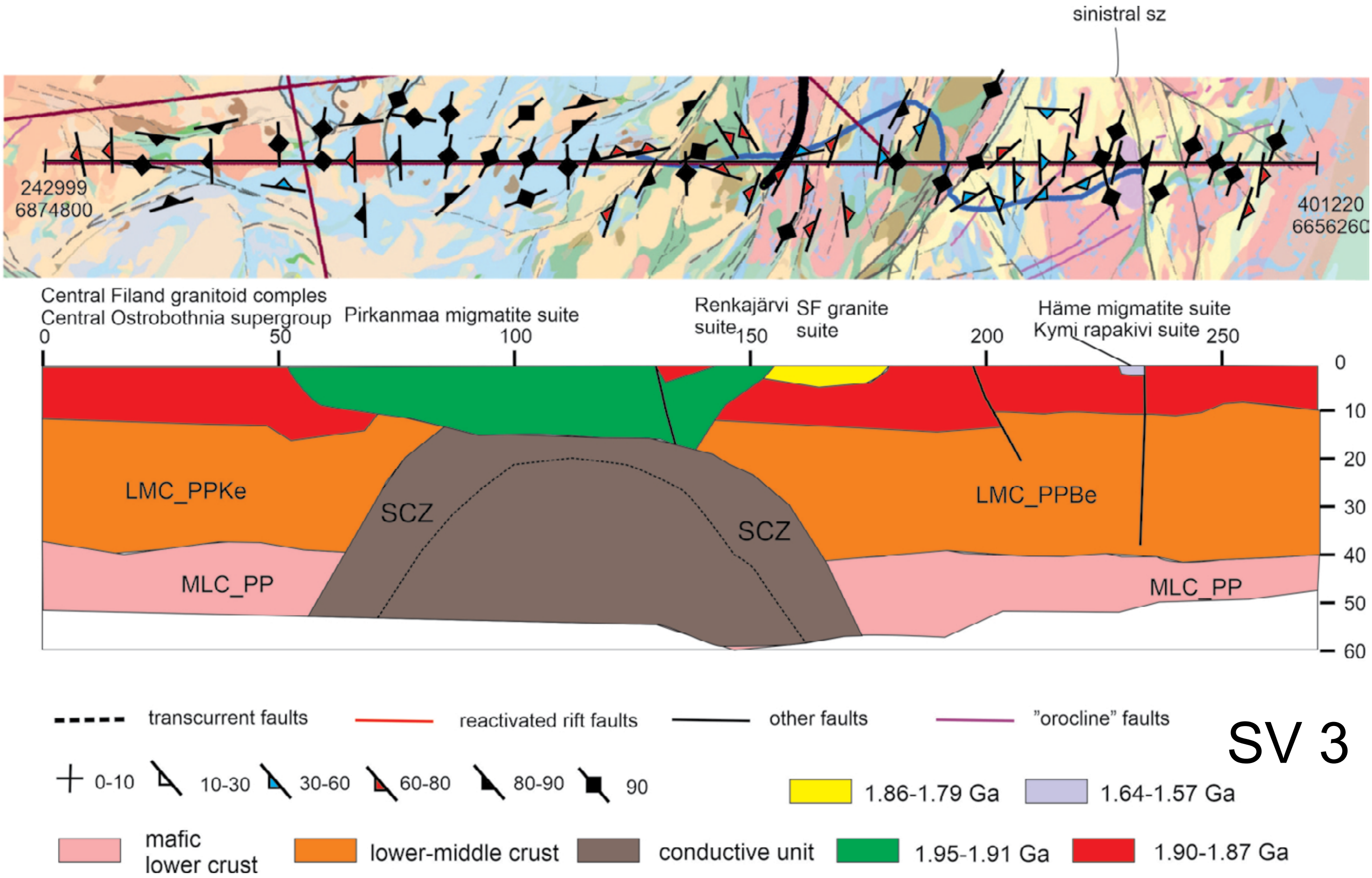


dextral sz
389011
6998855
349859
6731625
Central Finland granitoid comples
Central Ostrobothnia supergroup
Pirkanmaa migmatite suite
Renkajärvi suite
SF granite suite
Häme migmatite suite
LMC_PPKe
MLC_PP
SCZ
SCZ
LMC_PPBe
MLC_PP
transcurrent faults
reactivated rift faults
other faults
"orocline" faults
SV 2
0-10
10-30
30-60
60-80
80-90
90
1.86-1.79 Ga
mafic lower crust
lower-middle crust
conductive unit
1.95-1.91 Ga
1.90-1.87 Ga

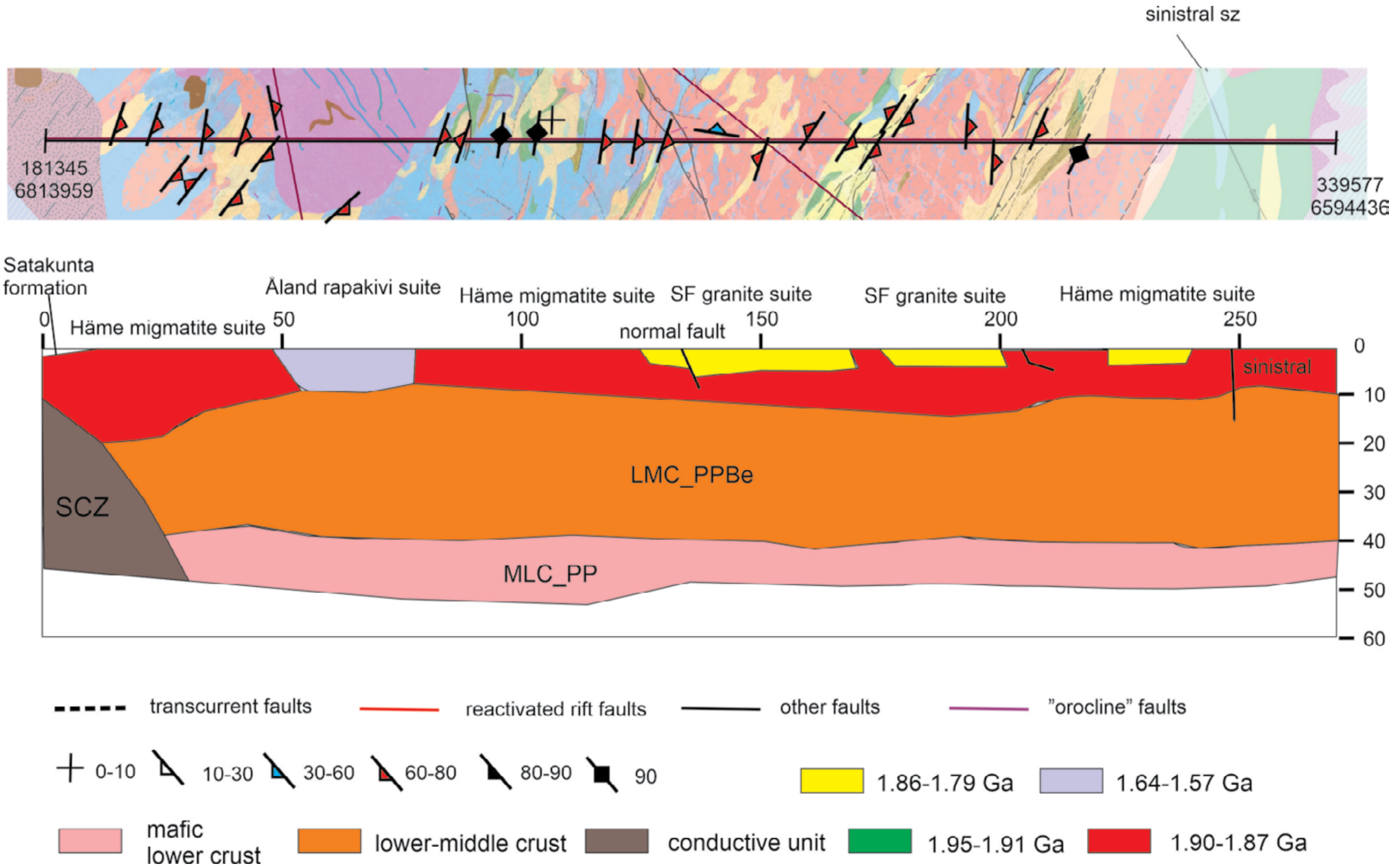


oblique dextral sz
dextral sz
277538
6859586
263954
6589316
Central Finland granitoid comples
Central Ostrobothnia supergroup
Pirkanmaa migmatite suite
Häme migmatite suite
SF granite suite
Häme migmatite suite
SF granite suite
LMC_PPKe
SCZ
SCZ
LMC_PPBe
MLC_PP
MLC_PP
transcurrent faults
reactivated rift faults
other faults
"orocline" faults
0-10
10-30
30-60
60-80
80-90
90
1.86-1.79 Ga
SV 2a
mafic lower crust
lower-middle crust
conductive unit
1.95-1.91 Ga
1.90-1.87 Ga

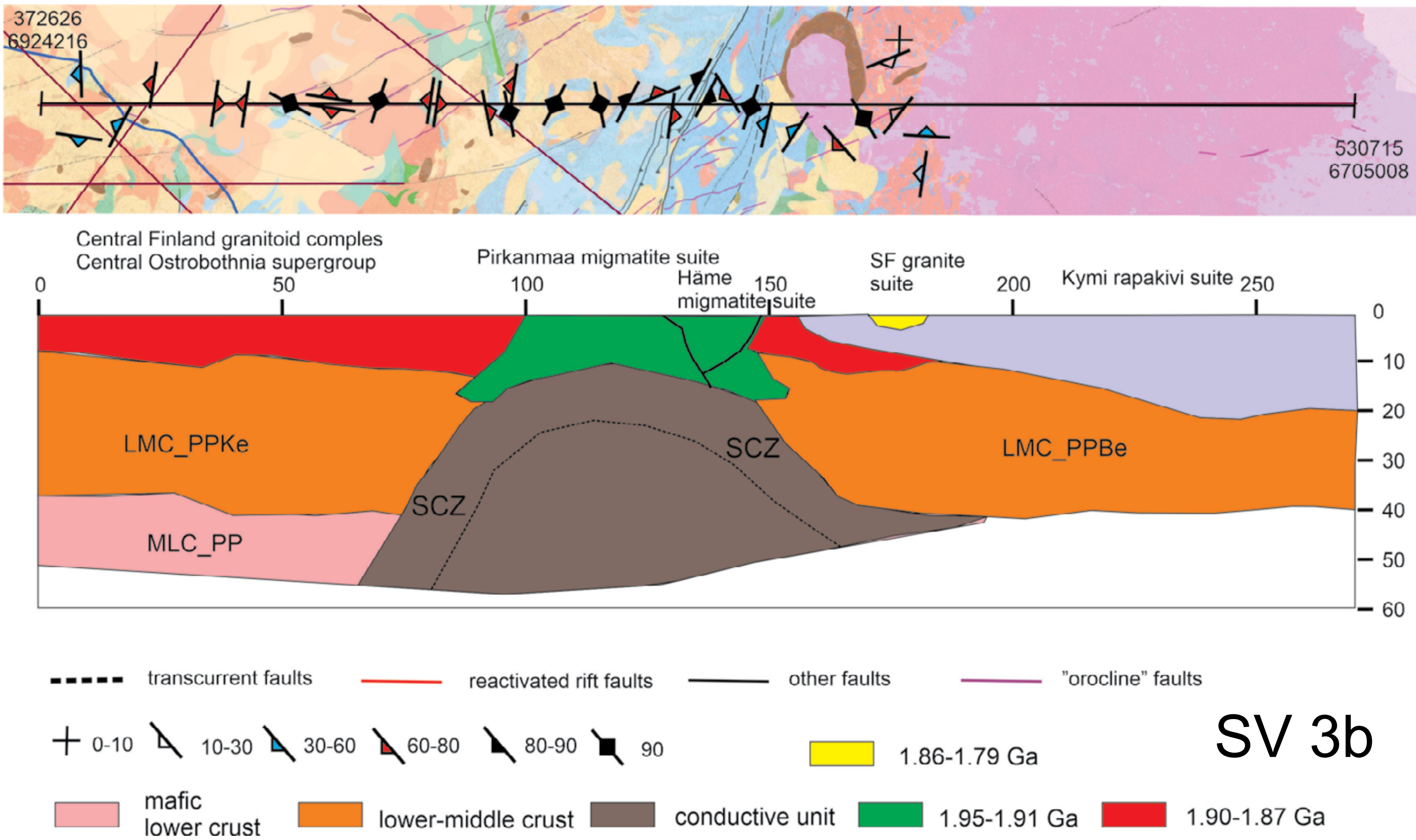

431652
6955570
417629
6685430
Central Finland granitoid comples
Central Ostrobothnia supergroup
Pirkanmaa
migmatite suite
Häme
migmatite suite
SF granite suite
Häme migmatite suite
0
50
100
150
200
250
0
10
20
30
40
50
60
LMC_PPKe
MLC_PP
SCZ
SCZ
LMC_PPBe
MLC_PP
transcurrent faults
reactivated rift faults
other faults
"orocline" faults
0-10
10-30
30-60
60-80
80-90
90
1.86-1.79 Ga
mafic
lower crust
lower-middle crust
conductive unit
1.95-1.91 Ga
1.90-1.87 Ga
SV 2b

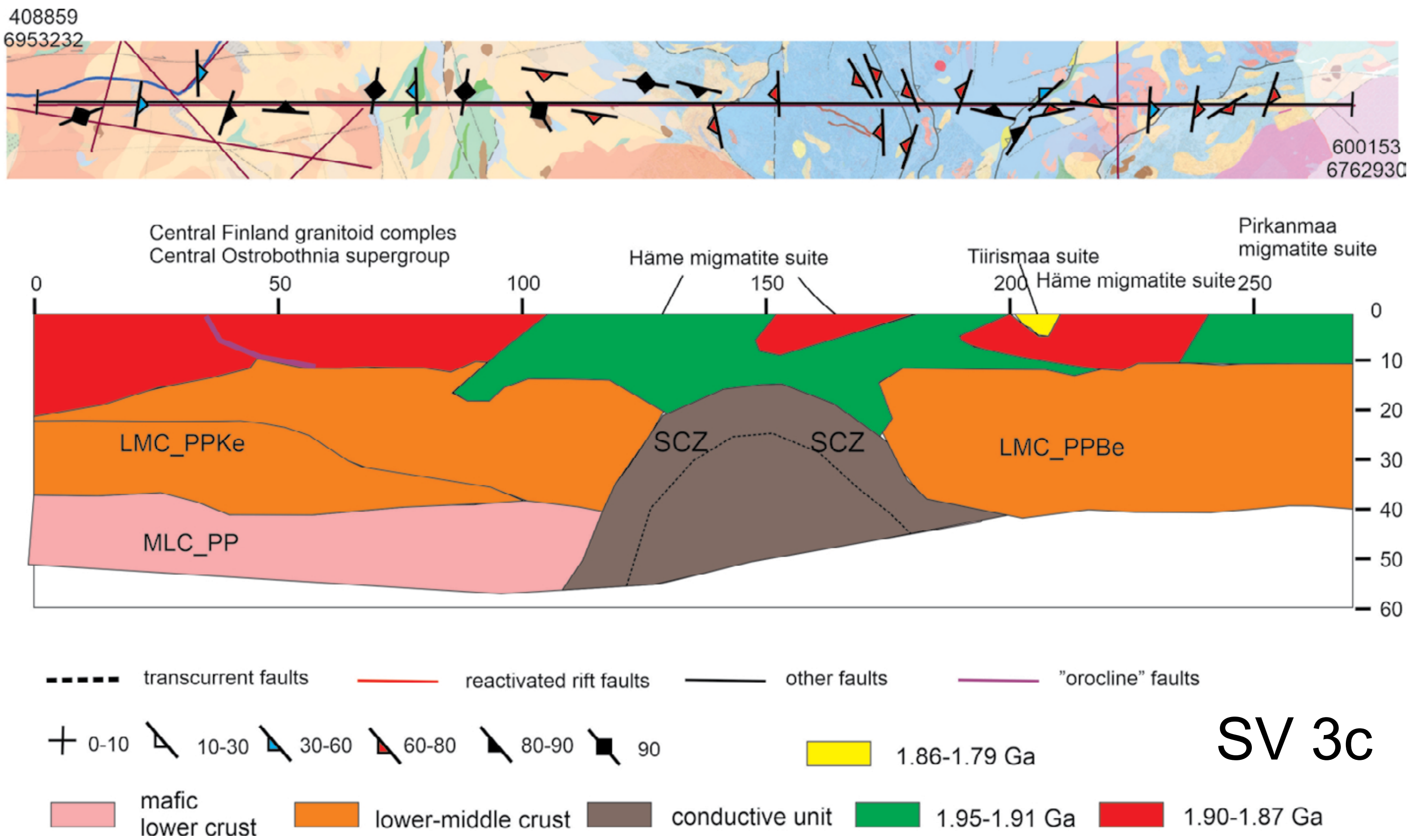

sinistral sz
242999
6874800
401220
6656260
Central Filand granitoid comples
Central Ostrobothnia supergroup
Pirkanmaa migmatite suite
Renkajärvi suite
SF granite suite
Häme migmatite suite
Kymi rapakivi suite
0
50
100
150
200
250
0
10
20
30
40
50
60
LMC_PPKe
SCZ
SCZ
LMC_PPBe
MLC_PP
MLC_PP
transcurrent faults
reactivated rift faults
other faults
"orocline" faults
0-10
10-30
30-60
60-80
80-90
90
1.86-1.79 Ga
1.64-1.57 Ga
mafic lower crust
lower-middle crust
conductive unit
1.95-1.91 Ga
1.90-1.87 Ga

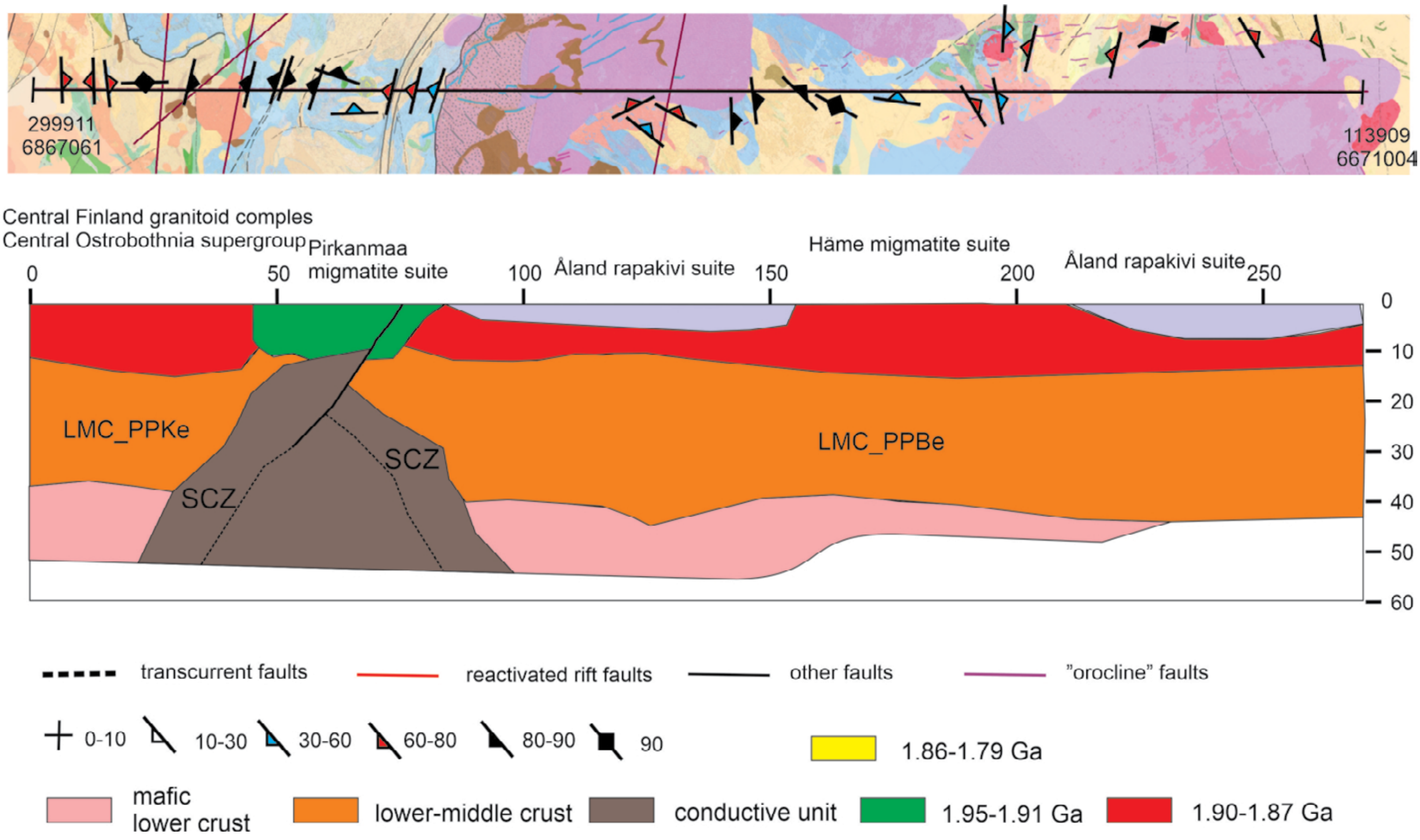
SV 3


sinistral sz
181345
6813959
339577
6594436
Satakunta formation
Häme migmatite suite
Åland rapakivi suite
Häme migmatite suite
SF granite suite
normal fault
SF granite suite
Häme migmatite suite
0
50
100
150
200
250
0
10
20
30
40
50
60
sinistral
SCZ
LMC_PPBe
MLC_PP
transcurrent faults
reactivated rift faults
other faults
"orocline" faults
0-10
10-30
30-60
60-80
80-90
90
1.86-1.79 Ga
1.64-1.57 Ga
mafic lower crust
lower-middle crust
conductive unit
1.95-1.91 Ga
1.90-1.87 Ga

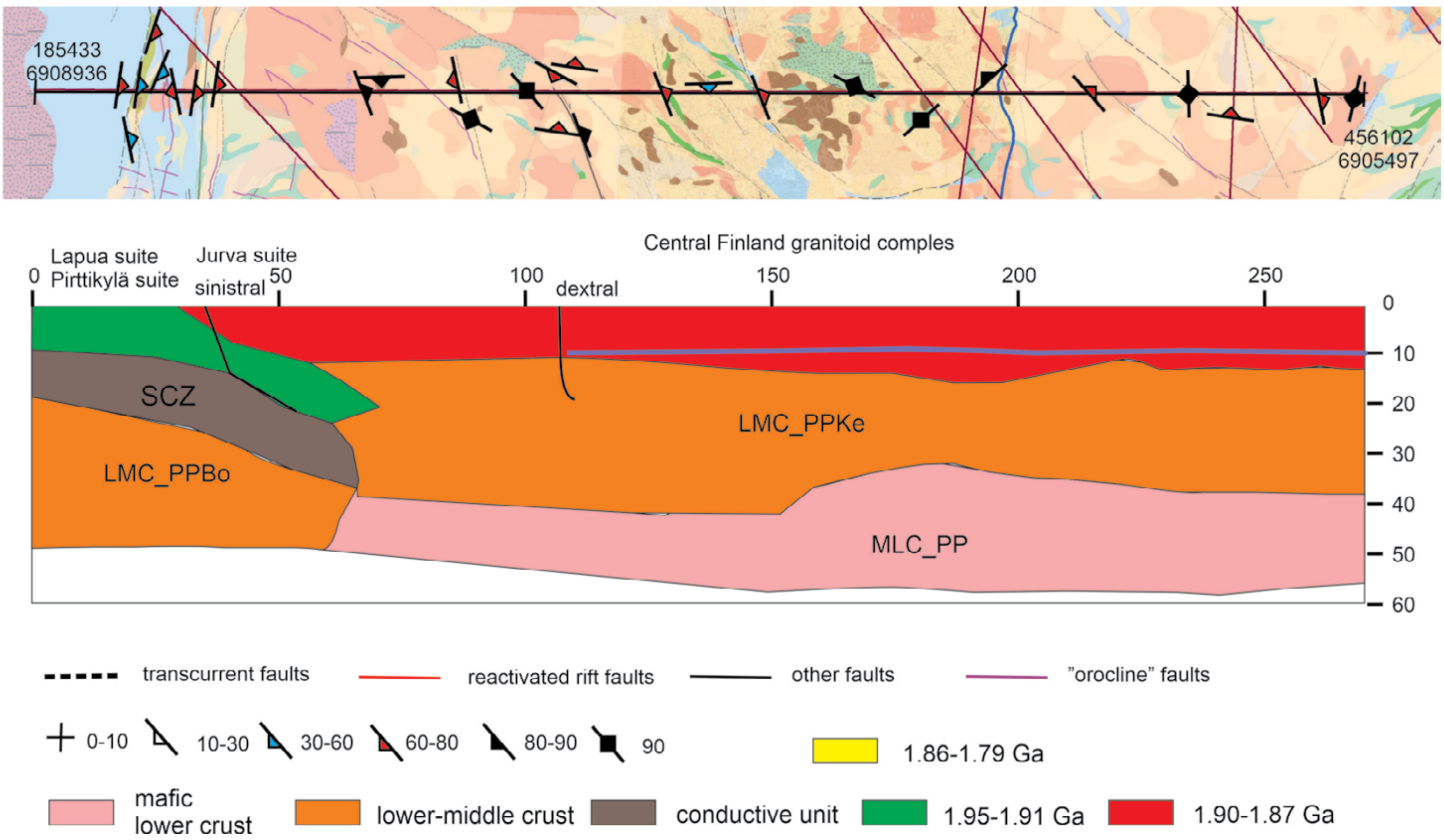
SV 3a


372626
6924216
530715
6705008
Central Finland granitoid comples
Central Ostrobothnia supergroup
Pirkanmaa migmatite suite
Häme
migmatite suite
SF granite
suite
Kymi rapakivi suite
0
50
100
150
200
250
0
10
20
30
40
50
60
LMC_PPKe
SCZ
SCZ
LMC_PPBe
MLC_PP
transcurrent faults
reactivated rift faults
other faults
"orocline" faults
0-10
10-30
30-60
60-80
80-90
90
1.86-1.79 Ga
mafic
lower crust
lower-middle crust
conductive unit
1.95-1.91 Ga
1.90-1.87 Ga
SV 3b

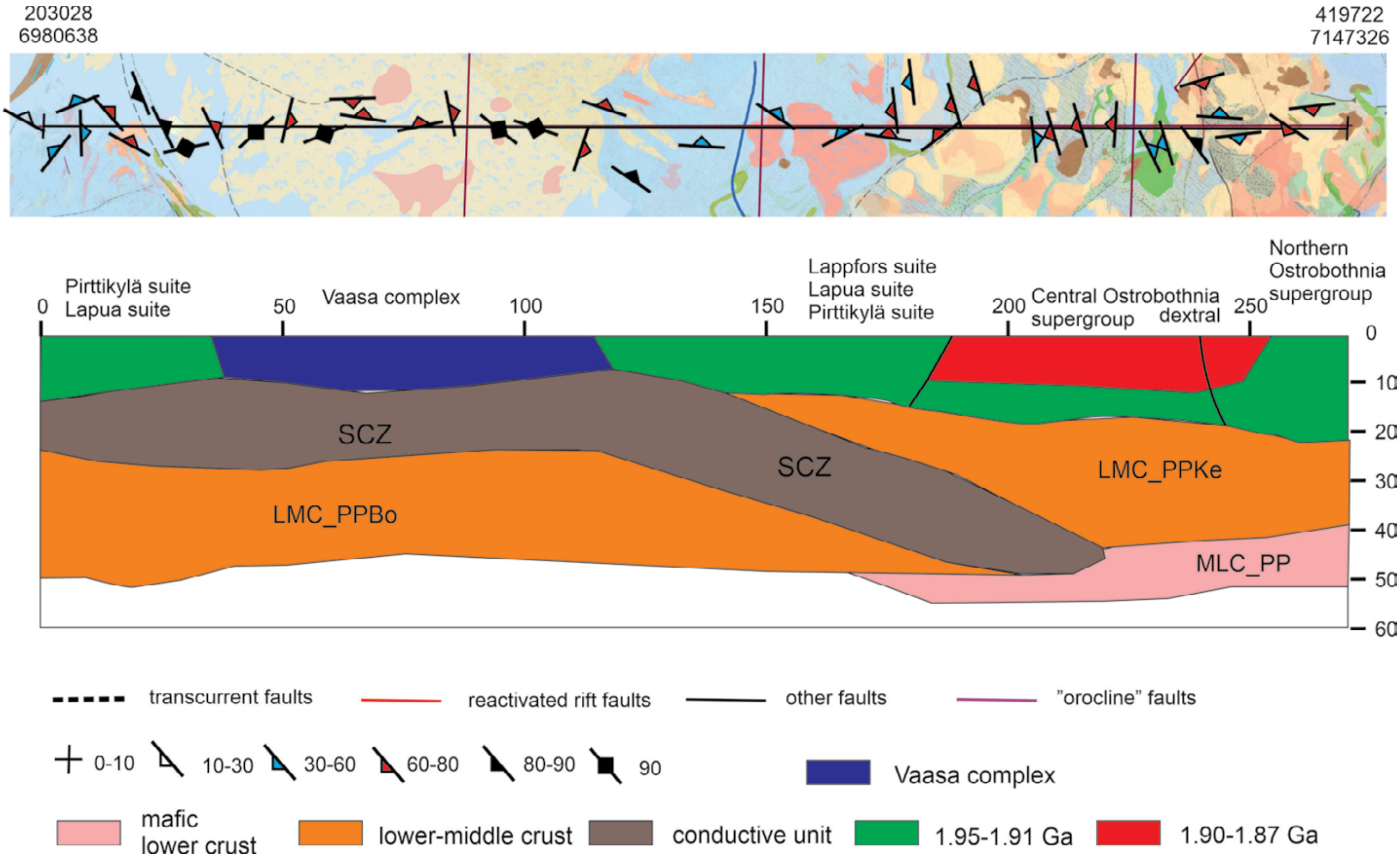

408859
6953232
600153
6762930
Central Finland granitoid comples
Central Ostrobothnia supergroup
Häme migmatite suite
Tiirismaa suite
Häme migmatite suite
Pirkanmaa
migmatite suite
0
50
100
150
200
250
0
10
20
30
40
50
60
LMC_PPKe
SCZ
SCZ
LMC_PPBe
MLC_PP
transcurrent faults
reactivated rift faults
other faults
"orocline" faults
0-10
10-30
30-60
60-80
80-90
90
1.86-1.79 Ga
mafic
lower crust
lower-middle crust
conductive unit
1.95-1.91 Ga
1.90-1.87 Ga
SV 3c


299911
6867061
113909
6671004
Central Finland granitoid comples
Central Ostrobothnia supergroup
Pirkanmaa migmatite suite
Åland rapakivi suite
Häme migmatite suite
Åland rapakivi suite
0
50
100
150
200
250
0
10
20
30
40
50
60
LMC_PPKe
SCZ
SCZ
LMC_PPBe
transcurrent faults
reactivated rift faults
other faults
”orocline” faults
0-10
10-30
30-60
60-80
80-90
90
1.86-1.79 Ga
mafic lower crust
lower-middle crust
conductive unit
1.95-1.91 Ga
1.90-1.87 Ga

SV 4


185433
6908936
456102
6905497
Lapua suite
Pirttikylä suite
Jurva suite
sinistral
dextral
Central Finland granitoid comples
0
50
100
150
200
250
0
10
20
30
40
50
60
SCZ
LMC_PPBo
LMC_PPKe
MLC_PP
transcurrent faults
reactivated rift faults
other faults
”orocline” faults
0-10
10-30
30-60
60-80
80-90
90
1.86-1.79 Ga
mafic lower crust
lower-middle crust
conductive unit
1.95-1.91 Ga
1.90-1.87 Ga

SV 5



203028
6980638
419722
7147326
Pirttikylä suite
Lapua suite
Vaasa complex
Lappfors suite
Lapua suite
Pirttikylä suite
Central Ostrobothnia supergroup
dextral
Northern Ostrobothnia supergroup
0
50
100
150
200
250
SCZ
SCZ
LMC_PPBo
LMC_PPKe
MLC_PP
transcurrent faults
reactivated rift faults
other faults
"orocline" faults
0-10
10-30
30-60
60-80
80-90
90
Vaasa complex
mafic lower crust
lower-middle crust
conductive unit
1.95-1.91 Ga
1.90-1.87 Ga

SV 6

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